THEORY AND APPLICATION OF SHAPED CHARGES

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THEORY AND APPLICATION
OF
SHAPED CHARGES

by

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CHAPTER I

INTRODUCTION

Although much has been written concerning shaped charges, adequate coordination of this material has not been effected and as a result, many different sources must be scrutinized to determine what has been accomplished in the field.

It is the purpose of this work therefore to effect such coordination and to bring under one cover a comprehensive survey of the literature including the most recent developments.

THE SHAPED CHARGE DEFINED

"Shaped charge" is the name commonly applied to any explosive charge which is hollowed out on the side facing the object to be attacked. The penetration produced on detonating such a charge is much greater than if a solid charge of the same outside dimensions were used.

The essential difference between the effect obtained with a shaped charge and solid charges is that whereas the solid charge exerts a general shattering effect, the hollow charge exerts a directional, piercing effect and punches a hole in the hardest of steel or the most resistant of concrete. If the shaped portion of the charge is lined with a thin metal, an enormous increase in penetrating power is obtained; and if, in addition, the charge is held away from the target a fixed distance called the standoff distance, the penetrating power is increased still further.

The cavity has been given a variety of geometrical shapes, e.g., cones, hemispheres, paraboloids, pear shapes, trumpet shapes, and linear V-shaped wedges, and the associated phenomenon is variously called the Munroe effect, the Neumann effect, the cavity effect, the hollow charge effect, the directed blasting effect, and of course the shaped charge effect. The use of the term "shaped charge" was originally adopted by the military during World War II in an effort to camouflage the true identity of the charge, for to the uninformed, a shaped charge might have

Fig. 1. Effect of different charges is shown by four steel blocks which were actually fired upon in experiments. The charges above the blocks are wooden replicas. (50)

any configuration.

It should be pointed out that the true Munroe effect is that which is obtained by the use of an unlined, hollow charge, whereas whenever the term shaped charge is used, a lined, hollow charge is generally implied. Certain authorities in this field feel that the shaped charge effect should be called the metallic jet effect.

Fig. 1 shows four rectangular steel blocks, each of which has been struck by a different type of explosive charge. The right-hand block has scarcely been dented by a conventional solid charge. The next block has a small hole in it caused by an unlined, conical shaped charge. The third block from the right shows the effect of a metal-lined shaped charge, the charge having been held against the steel block. The fourth block shows the deepest penetration caused by the same lined charge which has now been held away from the steel block a fixed distance, which as was previously mentioned, is called the standoff distance, or simply standoff.

A striking illustration of the directional effect of the hollow charge is shown by Fig. 2 in which a shaped charge was fired vertically upward in a night demonstration at Aberdeen Proving Grounds.

Fig. 3 shows the essential features of two types of shaped charges with hemispherical and conical lined cavities. Hollow conical liners for penetration and hollow V-shaped liners for cutting have been encountered most frequently and have been most thoroughly investigated. It is desired to point out that the mechanism of jet formation shown in Fig. 3 is the old "spall theory" which has been found to be erroneous, and has since been superseded by more modern theories. The theory of jet formation is taken up in detail in Chapter II.

EARLY HISTORY

Mining engineers have long known that some of the force of an explosive charge can be concentrated on a small area by cutting out a little "chunk" of dynamite before placing the stick against the object

Fig. 2. Night photograph of a shaped charge fired vertically upward during a demonstration at Aberdeen Proving Grounds. Height of jet is approximately 250 feet. (19)

to be destroyed. The earliest known reference to this was made in 1792.

Some of the earliest recorded work which gave evidence of this phenomenon was done in 1883 by Max von Forster, engineer and superintendent of the gun-cotton factory of Max Wolff and Company of Walsrode, Germany. In August 1884, Lieutenant John P. Wisser, U. S. Army, translated for Van Nostrand's Engineering Magazine (54) an earlier article

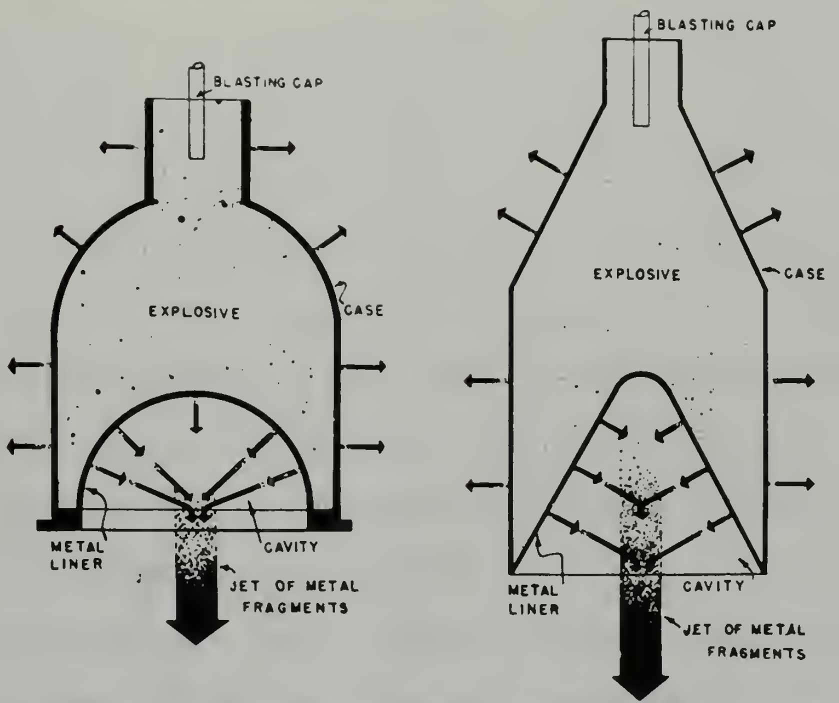


Fig. 3. Sketches of shaped charges with (a) hemispherical and (b) conical metal-lined cavities showing mechanism of formation of Munroe effect. (25)

by von Forster describing experiments conducted to determine in what manner compressed gun-cotton should be applied to obtain the greatest and most useful effects. Von Forster attacked lead cylinders with cylindrical charges of gun-cotton, both solid and having cylindrical hollows as shown in Fig. 4.

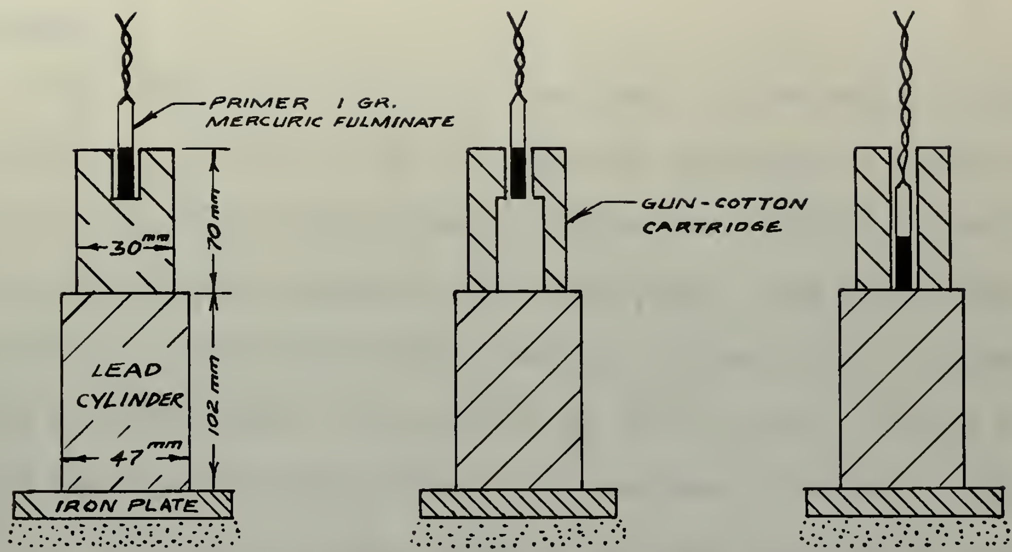


Fig. 4. Experimental set-up used by Max von Forster. (54)

He made the important discovery that the effect on the object attacked was greater in the case of hollow charges than in solid ones of the same outside dimensions, even though the solid ones contained more explosive. He realized that if he could give the gases of the detonated gun-cotton a fixed direction toward the object under attack, the destructive effect would be increased.

Von Forster stated that his experiments furnished two means of attaining this end. First, the primer must always be placed on the side opposite the charge, as the detonation of the primer gives the detonation gases a direction away from itself and toward the side opposite. A second method of giving the detonation gases a fixed direction consisted in furnishing the cartridge with a hollow opening, on the side opposite the primer and adjacent to the object to be destroyed.

He found that in explosions against wrought iron, a strong impression of the cross-section of the hollow opening of the cartridge appeared which was twice the depth of the impression produced by a solid

cartridge.

Von Forster also made what he believed to be an entirely original observation that if a piece of compressed gun-cotton is placed on a piece of iron, an accurate impression of the form of the under surface of the gun-cotton is produced by the detonation. Every angle, every projection and every indentation present in the gun-cotton is impressed on the underlying iron. Von Forster held that the gases produced have copied the form of the gun-cotton and transferred or transmitted it to the iron, and "that the gases acting on the iron have occupied exactly the same space, and no more, than the solid explosive previously occupied." Hence he concluded that "only the gases evolved by the very undermost layer of gun-cotton act on the iron, while the others are lost."

In February of 1885, Dr. Charles E. Munroe, generally conceded to be the most prominent pioneer in this field, relates in his "Notes on the Literature of Explosives" (36) of how he had encountered Lt. Wisser's translation of von Forster's article. Munroe states that the author's explanation for the cause of the impressions made by the compressed gun-cotton was "as novel as the observation."

Munroe claims that, before meeting with von Forster's article, he had seen similar impressions produced in iron by the detonation of disks of gun-cotton upon iron (35), but that he considered them due to projection; the residual gun-cotton being driven into the metal by the explosion of the original mass. He went on to say (39):

> "Of course, we are met here by the difficulties that this hypothesis implies: (1) That the pressure exerted upon the residual mass of gun-cotton is transmitted more rapidly than the explosive reaction is propagated within the mass, and (2) it implies also a great rigidity or coherence for this mass. The last condition requires that which is a property of masses of matter when moving at high velocities

as in the well known candle experiment, and in the cutting of steel by soft iron and the like. The difficulties presented in the first condition do not seem so great as those in Lieutenant von Forster's hypothesis.

"Some months subsequent to this, (1886) Commander T. F. Jewell, U. S. Navy, read a paper before the American Association for the Advancement of Science on the 'Apparent resistance of a body of air to a change of form under sudden compression,' and presented as an example of the action of this phenomenon, an iron plate upon which a disk of gun-cotton had been detonated. The letters U. S. N. and the figures 1884 had been indented in the surface of the gun-cotton, and similar letters and figures were found indented in the iron plate. He held that this indentation was due to the fact that the air enclosed in the letters and figures in the disk acted, under the sudden and enormous pressure to which it was subjected, like a hard body and was thus driven into the iron.

"In a later pamphlet (Berlin, 1886) von Forster again states that the gases generated by the detonation of the gun-cotton have, in the first instant, and as long as they exert their maximum force, the exact form and occupy the same space as was occupied by the gun-cotton before detonation and thus they produce an exact impression on the plate of the surface of the gun-cotton in contact with it, and he also says that the suddenness with which the power is exerted is shown by placing a leaf between the gun-cotton disk and the iron, for after detonation the whole frame or skeleton of the leaf will be found raised upon the iron. He explains that this is due to the larger as well as the smaller ribs of the leaf protecting the underlying parts of the iron while the thinner parts between could not yield such protection, and under them the impression is deeper."

This was the condition of the subject when Munroe again began to study it experimentally in 1886 while at the Naval Torpedo Station, Newport, R.I. in the capacity of Chemist to the Torpedo Corps, U. S. Navy. He first placed upon iron plates some gun-cotton disks in which figures and letters were indented, and upon detonation obtained impressions on the plates in which these were also indented. He next used disks having raised letters and figures and obtained impressions in which these were also raised. Next he cut deep channels in the disks, of various forms, taking care that they always communicated with the outer air so that there

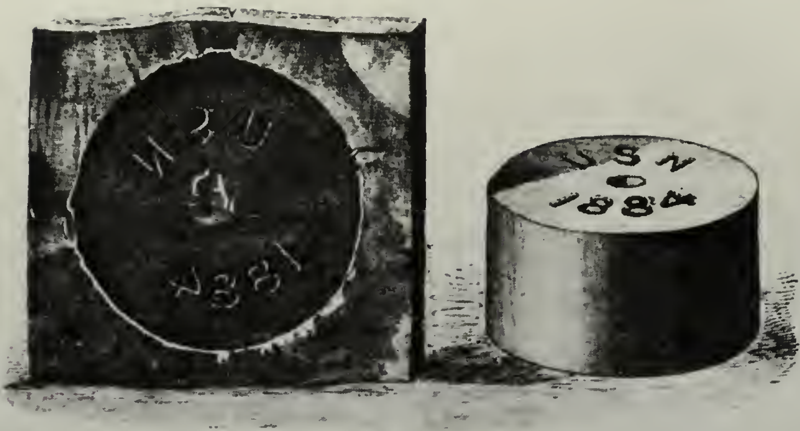
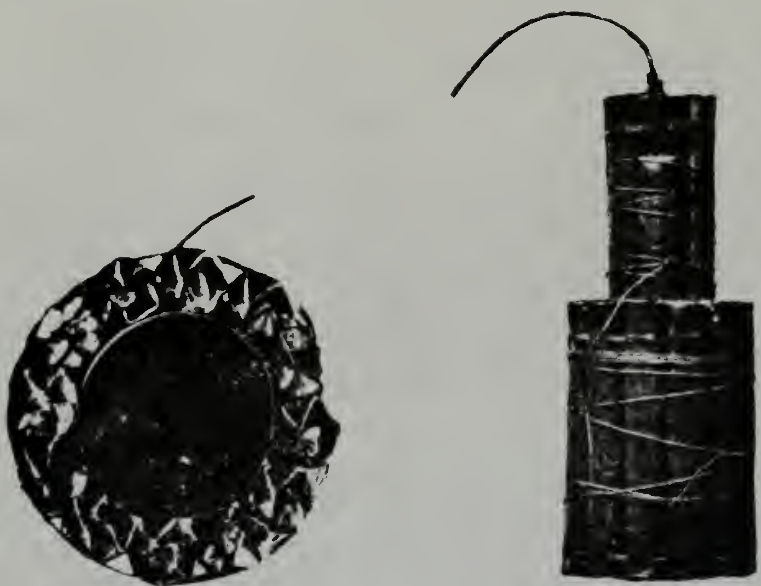


Fig. 5. Disk of gun cotton (right) and iron plate (left) upon which a disk has been detonated. The letters and figures stamped in the disk are reproduced in precisely the same relation on the iron plate. (40)



View from below

Elevation

Fig. 6. Hollow dynamite charge as constructed by Munroe in 1891 for blasting a hole in a safe. Sticks of dynamite were lashed around the outside of a tin can resulting in a cylindrical cavity. (40)

would be no air confined in them, and again the impressions were exactly reproduced in the iron. He next filled the indented letters and figures, in disks such as Jewell had used, with paraffin and with vaseline, so that the material was flush with the surface of the disk, and, on detonation, the letters and figures were found to have been obliterated. He next struck, with stamps, similar letters and figures on an iron plate. This plate was laid face downward on another iron plate and a lettered gun-cotton disk was placed on the upper plate and detonated. The result was, that while the gun-cotton disks produced the usual indented letters on the back of the top plate of iron, the top plate in whose letters and figures air was also confined and which was subjected to the same blow, produced raised letters and figures on the iron plate on which it rested.

According to Munroe (39) in a talk given before The Newport Natural History Society on October 20, 1886:

> "These last three experiments certainly seem to prove that the resistance of air to compression has nothing to do with this action. Again, when we consider how enormous the pressure to which this air is subjected becomes, we must believe that, no matter how suddenly the form is applied, the air must undergo some compression, yet we find that the indentations in the iron are often nearly as deep as those in the gun-cotton.
>
> "In considering von Forster's hypothesis, we are willing to admit that the gases at the time of detonation possess the exact form and occupy the same space as the guncotton from which they are formed provided the change takes place instantaneously. But it does not; in fact it occupies so appreciable a period of time, that the rate of propagation of the detonation in it has been measured. Apart from this and even granting it, it will be observed that von Forster does not explain how the impression is to be produced by the gas. If the gas moves as a coherent mass, then the impressions should be the reverse of what we get.
>
> "From my recent experiments, I am the more strongly convinced that the effect is a purely ballistic one and that while the base of the gun-cotton, or its products, are projected as a whole against the plate, where the intervening

spaces are the greatest, there we have the greatest indentation. This is true, also, in the leaf experiment which has been exquisitely reproduced. The varying thicknesses of the leaf vary the distances through which the material is projected and hence the form and texture is reproduced in the impression.

"I take pleasure in exhibiting the specimens described and also two others which I have produced today. . . ."

In another test (40) Munroe soaked several cylinders of gun-cotton in water and bored holes of various diameters and depths into them, including one with a 1-3/4 inch hole bored completely through the cylinder. These wet disks were then placed on an iron plate and a similar dry disk of gun-cotton was placed on each as a primer. Upon firing, it was found that the deeper and wider the holes in the gun-cotton, the deeper and wider were the holes produced in the iron plate. In the case of the completely perforated gun-cotton cylinder, the iron plate was found to be completely perforated.

Munroe also made impressions of leaves, pieces of lace, coins, pieces of wire gauze, etc. on a gun-cotton disk and on firing, found that the objects were reproduced upon an iron plate with utmost fidelity.

In 1890, a commission was appointed by Congress for the purpose of determining the best method of safe and vault construction with a view to renewing or improving the vault facilities of the Treasury Department. Prof. Charles E. Munroe, then at the U. S. Naval Torpedo Station, Newport, R. I., was called upon by this commission to demonstrate how safes might be successfully attacked. Among the many experiments conducted by Munroe and his assistant, First Lieutenant Samuel Rodman, Jr., U. S. Army, to demonstrate the resistance of safes and vaults then in production and use, was one made in December 1891 upon a cubical safe with walls 4-3/4 inches thick, made up of plates of iron and steel.

For this test, Munroe assembled what is undoubtedly the first practical shaped charge, and unwittingly incorporated into it a metal liner in the form of a tin can. This hollow charge, shown in Fig. 6, was made by tying sticks of dynamite around and upon the closed end of a tin can. (45) The aggregate weight of the dynamite was 9-1/2 pounds. When the charge was placed upon the safe, with the open mouth of the can against the safe, and detonated from the opposite end, a hole 3 inches in diameter was blown clear through the 4-3/4 inch wall, upon which a solid charge of the same weight and material had previously produced no material effect.

Another prominent, but somewhat later, worker in this field was Egon Neumann who claimed discovery of the effect in the Zeitschrift für angewandte Chemie of November 24, 1911, for himself and his co-workers. He says "We have found in the last few months that if a hollow be made in an explosive cartridge on the side towards the object to be blasted, the effect is increased four- or five-fold."

It appears that Neumann was probably the first person to use a conical cavity in shaped charges, He also used a metal liner, but apparently did not appreciate the sizeable increase in penetrating power resulting from its use. He, like Munroe before him, apparently used it as a means of giving the desired shape to the cavity, for he indicates that no detrimental effects result if the liner is not removed before firing.

In 1915, in his book on Explosives, Arthur Marshall originally ascribed credit for the discovery of the hollow charge effect to Neumann. However, upon learning of Munroe's much earlier work, he made public his

error and gave credit for the discovery to Munroe. (28)

Although the shaped charge effect had been known for a good many years, all nations generally were relatively slow in adapting it to military or industrial use. Patents for Neumann's discovery of the hollow charge effect had been taken out in Germany in 1910 (Ger. Pat. Anm. W. 36,269 of 14.12.1910) and in England in 1911 (Eng. Pat. 28,030 of 13.12.1911), yet as late as 1920, A. Marshall stated that "No practical use has apparently been made of this discovery, but it is of interest as throwing a light on the nature of the detonation wave." (28)

Not until about 1939 did the U. S. Ordnance Department begin to apply the shaped charge principle in practical armor-piercing ammunition, and its subsequent development and utilization during World War II was one of the most important scientific advancements made in the field of explosives during that war. The work of United Nations and Axis scientists in the investigation of the principles and applications of the shaped charge placed modern warfare on a new basis. A number of new and devastating weapons were added which necessitated drastic changes in military tactics. This has been particularly emphasized during the current conflict in Korea when the tremendous initial advantage of the Red mass tank attacks was later almost nullified by United States infantry, vehicular, and air-borne anti-tank weapons incorporating the shaped charge. Communist tank movements soon became almost limited to night operations because of the lethality of the hard-hitting American shaped charge weapons.

Although the shaped charge received assiduous attention and tremendous impetus by the military during the World War II era, it was not without a limited degree of progress along non-military lines. Many

engineers and others who witnessed the shaped charge in action during World War II immediately foresaw great possibilities for it in the industrial world, and as soon as the veil of security was lifted sufficiently, applications for a variety of patents incorporating the Munroe effect commenced to flow into the Patent Office.

The various methods in which the shaped charge has been utilized are taken up later in this work.

CHAPTER II

THEORY OF JET FORMATION

> "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."
>
> Lord Kelvin, Addresses, 1883

Until relatively recent years, the shaped charge effect was strictly a phenomenon. The various early investigators had hypothesized as to what occurred during the explosive reaction, but none had dared attack the mathematics of the problem.

Arthur Marshall in 1920 had to some extent correctly envisioned the sequence of events that gave the shaped charge its penetrating action when he stated (28):

> "The wave, consisting of such gas constantly renewed, advances through the explosive with a velocity of several thousand meters a second. Where the wave is in contact with the boundary of the explosive the gas flies off at right angles to the boundary and a fresh wave is formed. . . . . In the axis of the hollow of one of these bored-out charges the waves of highly compressed air come together with enormous violence, and necessarily produce a blast in the same direction as the original wave of detonation. This is not only much more intense than the original wave, because it is more concentrated, but it also lasts longer, with the result that the metal plate is carried right away. . . ."

Although satisfactory mathematical theories had been developed during World War II, it was not until June of 1948 that they found their way into the open literature. These theories, which are subsequently presented in this work, were developed during the latter part of 1943 and the early part of 1944 by Garrett Birkhoff of Harvard University,

Duncan P. MacDougall of the Naval Ordnance Laboratory, Emerson M. Pugh of Carnegie Institute of Technology, and Sir Geoffrey Taylor of Trinity College, England while working as a group in England and later in the United States. They are reproduced in the following discussion almost in their entirety.

Since most of the reliable data concerning shaped charges have been obtained with cone-lined charges, most of the following discussion will apply only to them.

Fig. 7. Hollow charge with wedge-shaped liner ready to be set off. (2)

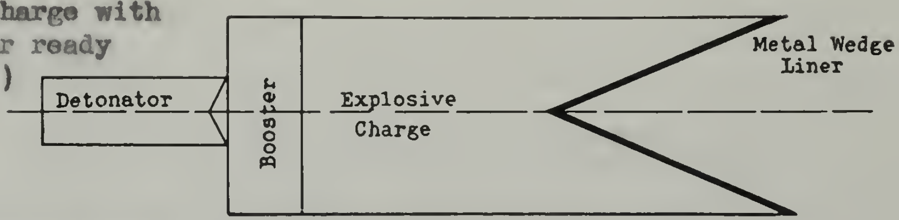
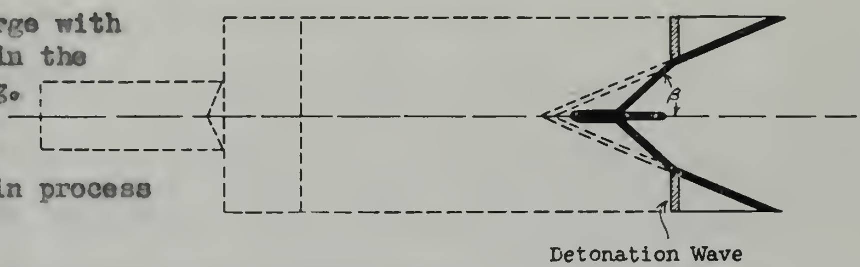


Fig. 8. Hollow charge with wedge-shaped liner in the process of exploding. Detonation wave has passed over most of the liner which is in process of collapsing. (2)



BASIC PRINCIPLES

The basic principles involved in the phenomenon are outwardly fairly simple, and using a crude analogy, can be likened to the squeezing of toothpaste out of a tube. The mechanism of cone collapse and the resulting formation of high speed jets have been revealed by means of high speed radiographs made during the explosion process.

Referring to Figs. 7 and 8, the detonation of the booster starts an explosive wave down the charge. When this wave reaches the apex of the lined cone, it suddenly produces very high pressures on the outside of this cone causing its walls to collapse. The forces are so great

that the strength of the metal liner has a negligible effect on the process, and the metal can be treated as though it were a perfect fluid. The explosive pressures on the outside cause the thin walls of the cone to move inward nearly perpendicular to their surfaces at high velocities. The moving metal retains a conical shape with the apex moving to the right along the axis. To the left behind the moving apex is found a section of thoroughly collapsed cone which contains metal only from the outer part of the cone. The inner part of the cone forms a jet which is squeezed out from the inner apex of the lining and travels at high speeds along the axis, to the right as shown in Fig. 8. In other words, the metal in the cone lining divides into two parts with the dividing surface between these two parts being a cone lying somewhere between the inner and outer surfaces of the original hollow cone. This has been confirmed in England by Kolsky, Snow and Shearman using bimetallic liners. (22) The metal from the outer cone forms into a slug that travels to the right at relatively slow speeds (1500 to 3000 ft/sec.) which are in the speed range of artillery projectiles. The metal from the inner cone on the other hand, forms into a jet that travels to the right along the axis at very high speeds (6000 to 30,000 ft/sec.). It is this jet that is solely responsible for producing deep penetrations. This extreme speed of 30,000 feet per second, however, is considerably smaller than the theoretical upper limit of jet velocity which as will be explained later, is equal to twice the detonation velocity. For the most highly brisant explosives, this is approximately 56,000 feet per second.

In 1945 in Bofors, Sweden, Professor W. Weibull photographed the detonation process of a shaped charge having a 60° cone of 1-mm. steel

plate and loaded with 200 grams of pentolite. The camera used had a speed of 5000 frames per second. His calculations showed the jet front to have a velocity of about 21,000 feet per second. The trailing slug was a separate solid piece with a velocity of about 2,100 feet per second. (15)

In the United States, flash radiographic techniques which permit excellent studies of shaped charge phenomena have been used extensively at the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. Fig. 9 illustrates quite clearly the mechanism of cone collapse. It should be noted that in this figure, the jet is travelling from right to left. In obtaining this series of radiographs, four different charges of identical size and construction were successively detonated and photographed using a Westinghouse Micronex unit. X-ray bursts of the order of one microsecond were used, only one flash radiograph being made for each charge at a different stage of the detonation process. Timing of the X-ray flash was accomplished by a Primacord clock technique.

Fig. 10 is another flash radiograph showing a metal jet perforating two parallel steel plates inclined at an angle of 45° with the direction of the jet. Here again, the jet is traveling from right to left. Note that the jet is to all intents and purposes undeviated in its passage through the plates. Excellent flash radiographs have also been taken of the detonation of electric blasting caps which also incorporate the Munroe effect.

Improved methods of instrumentation have done much toward improving our knowledge of the shaped charge phenomenon. One slight disadvantage of the flash radiograph technique is that it can only be used for

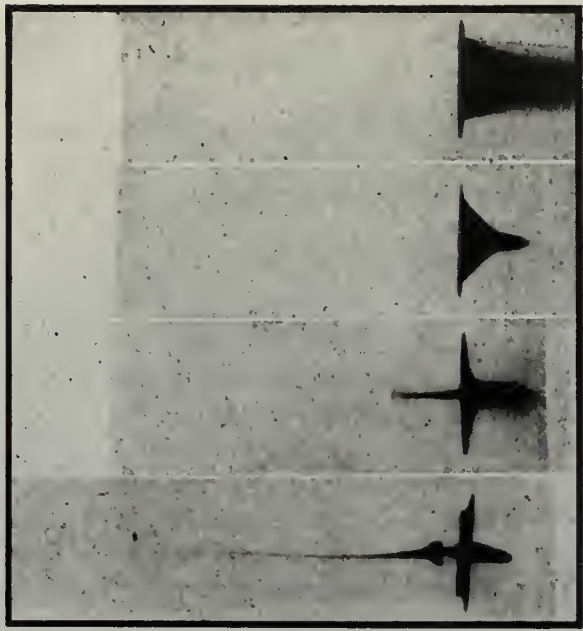


Fig. 9. Flash radiographs of metal-lined cavity charges. (a) Before detonation. The high explosive charge is cast about the 0.020-in. thick, 45° steel liner, and the charge diameter is the same as that of the base of the cone, not including the base flange. A 0.002-in. lead indicator strip is cemented along the top of the charge; (b) At approximately the instant the detonation reached the base of the conical liner; i.e., at the instant the last bit of charge detonated. The metal jet is seen inside the cone along the axis; (c) 4.8 microseconds after detonation reached base of cone; (d) 22.5 microseconds after detonation reached base of conical liner. The undisturbed base flange of the liner, the metal jet, and the slug are seen. (9)

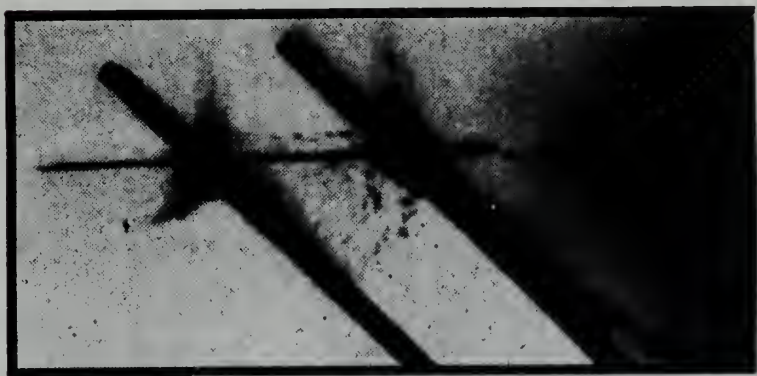


Fig. 10. Flash radiograph of a metal jet after perforating two $\frac{1}{8}$-in. mild steel targets set at 45° with the direction of the jet. The slug, seen at right, moves relatively slowly and performs no part in target penetration. (9)

the study of relatively small charges.

Extensive studies are being done at Carnegie Institute of Technology using super-high-speed camera techniques involving the electrical Kerr cell. By the use of transparent targets, excellent data may be obtained, even for relatively large charges. The Kerr cell technique is not suitable for the study of cone collapse, however.

For obtaining jet velocities, rotating mirror and rotating drum cameras are widely used. These produce streak pictures, from which slope measurements are made to yield jet velocities.

The collapse process of hemispherical liners has not been studied as extensively as have those of conical and wedge-shaped liners. A series of ingenious experiments conducted in England by Kolsky (23) indicate that a different phenomenon is involved here. The method employed by Kolsky was to enclose the explosive charge in a glass tube 1 cm. in diameter and separate the explosive from the liner with water layers of different thicknesses. The charges were fired into water and the fragments recovered. These experiments showed that in the case of hemispherical charges, the liner is turned inside out into a roughly conical shape with the rounded apex pointing in the direction of travel. Later the liner folds up behind this rounded apex which then breaks away from the rest of the liner due to its greater speed. Hence it is evident that a mechanism different from the hydrodynamic theory for conical and wedge-shaped liners is operative here. No mathematical theory has as yet been worked out for hemispherical liners.

MATHEMATICAL TREATMENT

An elementary mathematical discussion of the phenomenon will now

be presented. Consider again Figs. 7 and 8. We assume that, after the walls have received an original impulse from the detonation wave, the pressure on all sides of the liner quickly equalizes and the walls continue to collapse inward with no appreciable change in velocity. Because of the finite time required for the wave to travel from the apex of the liner to the base, the angle 2β between the moving walls is larger than that between the walls of the original liner.

Actually the effect of the detonation pressures acting for a very short distance is to give the liner a velocity V_0 which bisects the angle between the perpendicular to the original liner surface, and the perpendicular to the collapsing liner surface.

To show that V_0 bisects the angle APP' in Fig. 12, consider a coordinate system having a constant velocity such that the origin moves from P to P' in unit time. In these coordinates a steady-state condition exists in the region of the origin, with the liner flowing in along P'P, following a curved path and flowing out along PA. The curved path is caused by pressures on the liner from the detonation wave which have a constant distribution in these moving coordinates. The velocity of the liner passing through this region changes its direction but not its magnitude, since the pressure forces are everywhere perpendicular to the motion.

Let P'P and P'B (parallel to PA) represent, respectively, the entering and emerging velocities of the liner in the moving system. These are equal in magnitude. Since the velocity of the moving system is PP', the velocity of the collapsing liner in the stationary system is the vector sum PP' + P'B = PB = V_0. Also, since the triangle BPP' is isosceles and since P'B is parallel to PA, angle BPP' = angle PBP' = angle BPA. Therefore V_0 bisects the angle APP'.

The walls of the collapsing liner are two planes moving inward, as shown in Fig. 11.

From Fig. 12 the junction of these planes around A moves to B with a velocity

$$V_1 = [V_0 \cos 1/2(\beta-\alpha)/\sin \beta]$$

A moving observer stationed at this moving junction (point A) would find any point P in the upper plane moving with a velocity equal to the vector difference between the velocity of the walls and the velocity of the junction. Thus he would see the point P coming toward him with a velocity

$$V_2 = [V_0 \cos 1/2(\beta-\alpha)/\tan \beta] + V_0 \sin 1/2(\beta-\alpha).$$

Furthermore, as shown qualitatively by X-ray pictures and as shown in Fig. 13, he will see a "jet" moving off to the right and a "slug" moving to the left.

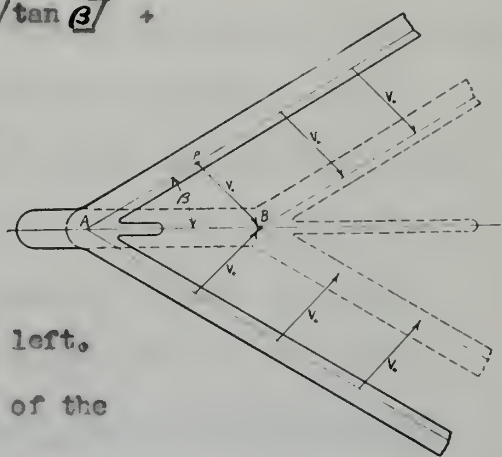


Fig. 11. Formation of jet and slug from a cone or wedge-shaped liner whose sides collapse with constant velocity V_0 as a result of the explosion of a charge that was in contact with the outer surface. The solid lines show conditions at an early instant of time, and the dotted lines show conditions after the walls have moved a distance equal to the velocity V_0. (2)

We now come to the crucial point of the discussion. As viewed by our observer, the whole process appears to be unchanged by the lapse of time. In hydrodynamic language it appears to be a "steady motion," from which it follows that we can use Bernoulli's equation

$$\int dp/\rho\,(p) + 1/2U^2 = \text{const}, \tag{1}$$

relating the pressure p and the velocity U. If the liner is nearly incompressible so that $\rho = \rho_0$ is constant, this reduces to the simpler and more familiar equation

$$p + 1/2\,\rho_0 U^2 = \text{const}. \tag{1'}$$

In either case, the pressure at any point in the fluid determines the velocity of the fluid at that point. Assume that the liner moves away from the exploded gases so fast that the pressure on its surface

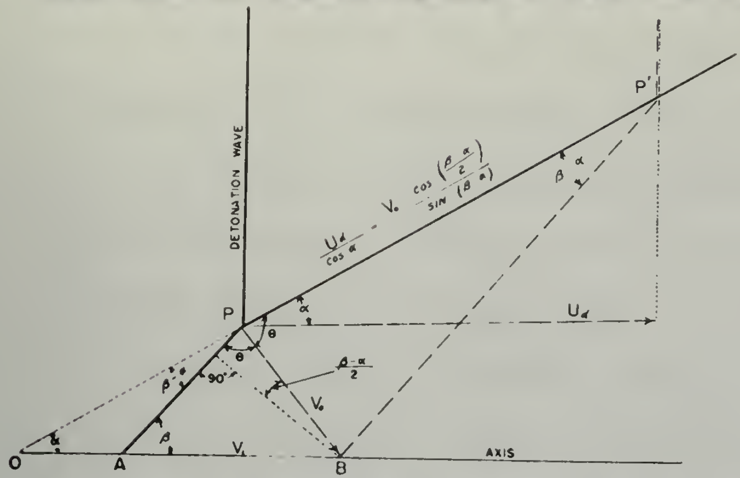


Fig. 12. Geometry of the collapse process. OPP' is the upper half of the original cone or wedge. AP, the collapsing section, is moving with a velocity V_0, whose direction bisects the angle APP'. The detonation wave (velocity U_d) will move from P to P' in unit time at which time $P'B$ will become the collapsing section. The junction A will move to B in unit time at a velocity

$$V_1 = V_0(\sin\theta/\sin\beta)$$
$$= V_0[\cos\tfrac{1}{2}(\beta-\alpha)/\sin\beta],$$

since $\theta = 90° - \frac{1}{2}(\beta-\alpha)$.
(2)

is very low and hence the pressures are constant on all of the surfaces of the collapsing liner. This is a well-known situation, and the boundary streamlines at constant pressure (hence velocity) are called "free streamlines." Hence, as viewed by the observer, the jet and slug will appear to recede with exactly the same speed, V_2, as the walls appear to approach; this is shown in Fig. 13. In particular, during collapse, the jet and slug will have exactly the same length.

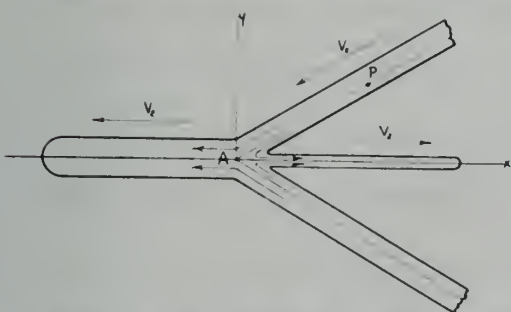


Fig. 13. Formation of jet and slug by a cone or wedge-shaped liner shown in Fig. 11 from the point of view of an observer stationed at the moving junction, A. (2)

This is observed experimentally.

Going back to the stationary system of coordinates, it is seen that the forward jet (traveling to the right in Fig. 13) has a velocity given by

$$V = V_1 + V_2$$

while the backward jet or "slug" (traveling to the left in the moving system of Fig. 13) actually has a small velocity to the right given by

$$V_s = V_1 - V_2$$

It may help to visualize the process to consider that: if the point P (fixed in the upper plane, Fig. 11) travels to point B (fixed in space) in unit time, the material from the inner surface of the upper plane included between PA and AB moves into the jet, and the front of the jet moves to the right a distance equal to PA + AB in the same time. Thus this material forms the very high velocity jet that is responsible for the deep penetrations. Its velocity is

$$V = V_0 \left(\frac{\cos 1/2(\beta - \alpha)}{\sin \beta} + \frac{\cos 1/2(\beta - \alpha)}{\tan \beta} + \sin 1/2(\beta - \alpha) \right). \qquad (2)$$

The material from the outer surface of each plane forms a slug and moves with the relatively low velocity

$$V_s = V_0 \left(\frac{\cos 1/2(\beta - \alpha)}{\sin \beta} - \frac{\cos 1/2(\beta - \alpha)}{\tan \beta} - \sin 1/2\,(\beta - \alpha) \right). \qquad (3)$$

The principal of the conservation of momentum determines the manner with which the material of the collapsing planes divides between the jet and the slug. Let m be the total mass per unit length of the two collapsing planes approaching the junction. Let m_j be that part of m going into the jet and m_s be that going into the slug. Then $m = m_j + m_s$. Equating the horizontal components of momentum before to those after passing the junction A in the moving coordinate system of Fig. 13,

$$mV_2 \cos \beta = m_s V_2 - m_j V_2$$

$$\left.\begin{aligned} m_j &= (m/2)(1 - \cos \beta) \\ m_s &= (m/2)(1 + \cos \beta) \end{aligned}\right\} \qquad (4)$$

According to this simple picture, the velocities of the jet and slug and their cross-sectional thicknesses are constant. Also, from the last equation, it may be seen that from weighings of the masses of the liner and the salvaged slug, the angle β can be evaluated without recourse to flash radiographic measurement.

The case of a conical liner may be treated in the same way. However, in this case the walls converge on the axis from all sides. The moving observer must travel at the same rate as in the case of the wedge. However, in order for the process to appear stationary to him, the total mass per unit distance along the axis must be constant. This is only approximately true in the case of a liner of constant thickness; to be exactly true, the liner thickness would have to be inversely proportional to the distance from the apex.

In the case of a plane detonation wave traveling parallel to the axis with constant speed U_d, we can even compute V_o from the fundamental relation

$$\frac{U_d}{\cos \alpha} = \frac{V_o \cos 1/2(\beta - \alpha)}{\sin (\beta - \alpha)}$$

which follows by pure geometry from Fig. 12. This replaces formulas (2)-(3) by

$$V = U_d \frac{\sin (\beta - \alpha)}{\cos \alpha} \left(\csc \beta + \operatorname{ctn} \beta + \tan 1/2 \, (\beta - \alpha) \right), \qquad (2')$$

$$V_s = U_d \frac{\sin (\beta - \alpha)}{\cos \alpha} \left(\csc \beta - \operatorname{ctn} \beta - \tan 1/2 \, (\beta - \alpha) \right). \qquad (3')$$

The jet velocity increases as the angle α decreases, since β also decreases. With such a detonation wave, the velocity approaches a maximum as α approaches zero. From equation (2')

$$V = 2\,U_d \quad \text{when} \quad \alpha = 0\,,$$

and the jet velocity cannot exceed twice the detonation velocity.

In the hypothetical case of a conical wave front, moving perpendicular to the surface of a conical liner so that it strikes all surfaces at the same instant, $\beta = \alpha$ and the velocities of the jet and slug from Eqs. (2)-(3) take the simple form

$$V = (V_o/\sin\alpha)(1 + \cos\alpha),$$

$$V_s = (V_o/\sin\alpha)(1 - \cos\alpha).$$

With wave fronts of this sort, the velocity of the jet could be increased indefinitely by decreasing the cone angle. However, as α tends to zero, the mass of the jet

$\left(m_j = (m/2)(1 - \cos\alpha) \right)$ and the momentum of the jet

$\left\{ m_j V = (mV_o/2)\sin\alpha \right\}$ both tend to zero.

Experiments have been conducted to change the shape of the detonation wave from planar to curvilinear in an attempt to make β equal α. (7) Inert aluminum disks 1-1/2 in. in diameter and 3/8-in. thick were inserted in 3-in. charges at varying distances from the top of the charge. The only effect produced was to impede the mechanism of jet formation when the disk was placed close to the cavity liner.

In summarizing, the mathematical theories presented above predict jet and slug velocities as in (2)-(3), (2')-(3'), and jet and slug masses as in (4) both for conical and wedge-shaped liners.

COMPARISON WITH EXPERIMENT

The preceding theoretical predictions are in rough agreement with observation, but with important exceptions. According to flash

radiographs, the collapse angle 2β is greater than the original cone angle and is approximately constant throughout the collapse process, which is in complete agreement with the theory. Further, these same radiographs, as well as some rotating drum camera measurements, show that the speeds of the front of the jet and of the slug are close to those predicted by Eqs. (2) and (3), respectively, but, contrary to prediction, the speed of the back, or last formed part of the jet, is considerably slower than that of the front. Also, contrary to predictions, an "afterjet" continues to be emitted after the walls have completely collapsed.

Since the collapse angle 2β has been approximately determined by flash radiography, Eqs. (4) can be checked experimentally if either the slug or the jet can be recovered after the explosion. While both can be recovered, it is fortunate that recovery of the slug is the easiest, since it can be made to yield more detailed information.

While charges bearing wedge-shaped liners do not give slugs that survive the detonation process and subsequent battering, charges bearing cone-shaped linings with apex angles of 60° or less do. These slugs have been recovered virtually undamaged by firing the charge into sawdust or water. They have been found to contain a smaller fraction of the original mass of the cone liner than Eqs. (4) predict. This is not surprising, since even qualitative inspection of the slug shows that the ideal collapse process, postulated in obtaining Eqs. (4), has not continued all the way to the base. If, however, before loading and firing the charge, the cone is sectioned by a series of cuts in planes parallel to the base, normal jet formation and performance is obtained.

Each section of the cone forms a corresponding portion of the slug. These portions, which were recovered as separate pieces, could be fitted together to form a normal appearing slug. By weighing each section before and after firing, the contribution of each part of the cone to the jet, and to the slug, was determined. It was found that for the upper part of the cone, the contributions to jet and slug agree with the values calculated from Eqs. (4) within the experimental uncertainty in the radiographic determination of the angle β. The percentage loss in weight increased, however, for the lower portions of the cone. This greater weight loss may be due in part to imperfect cone collapse near the base and the breaking off of some metal. Some of the increased loss, however, is certainly due to the formation of an additional length of jet from the slug after collapse is complete. This late formation of jet from the slug is clearly shown in the flash radiographs, and its existence is also indicated by the weight-loss relations. There has been considerable discussion as to why jet formation should continue for some time after collapse is complete.

It may be that a pressure wave in the exploded gases converges on the slug and squirts out the afterjet like toothpaste out of a tube. Metallurgical examinations on recovered slugs show that the material near the axes of these slugs has been heated almost to its melting point. (8) The pressure wave which may converge on a newly formed slug is undoubtedly the same as the pressure wave which is primarily responsible for the penetrations produced by these same charges without liners. Immediately after an unlined hollow charge has been detonated, the exploded gases stream into the cavity and converge onto the axis where

they are formed into a high speed jet. The effect produced by such a charge is the "Munroe effect" previously mentioned.

For such a mechanism to account for the observed velocity of the afterjet, it would be necessary for the secondary pressure wave, converging on the slug, to produce much higher pressures than one should expect from a charge like that shown in Fig. 7. Some other explanation is therefore needed.

Another possible explanation of the afterjet is that it may be pulled out by the primary jet which is continuous in the neighborhood of the slug throughout the process of its formation. This process of ductile drawing may be compared with the formation of fibers from molten glass or quartz. Experiments carried out by Bridgman have shown that many metals become enormously more ductile when subjected to intense pressure, and it appears conceivable that this great ductility might persist for at least a few microseconds after the pressure is released. If this latter mechanism is correct, it also would account in part for the velocity gradient found to exist in the jet, since acceleration of material from the slug would result in deceleration of parts of the jet already formed. While this latter mechanism seems most probable at present, it is possible that both mechanisms play some part.

More modern theories tend to give a better explanation of the "afterjet" effect. These theories, however, are still of a confidential nature and will not be included in this work.

SUMMARY

1. The mathematical theory presented predicts jet and slug velocities for both wedge-shaped and conical charges as in (2)-(3) and (2')-(3') respectively.

2. The mathematical theory also predicts jet and slug masses as in (4) for both wedge-shaped and conical liners.

3. The jet velocity increases as the cone angle decreases and approaches a maximum as the cone angle approaches zero. However, as the cone angle tends toward zero, the mass of the jet and the momentum of the jet both tend toward zero.

4. The jet velocity cannot exceed twice the detonation velocity.

5. No mathematical theory has as yet been worked out for the case of hemispherical liners. Experiments show that these liners are turned inside out during the detonation process; hence the hydrodynamic theory does not appear to apply.

CHAPTER III

THEORY OF PENETRATION

The process of penetration of a target material by a shaped charge jet is much like that of a high speed jet of water from a fire hose nozzle penetrating a bank of soft mud. Target material is splashed out at high velocities radially from the point of impact. The diameter of the hole produced is considerably greater than, and is not directly related to, the diameter of the jet, but is more closely related to the energy delivered by the jet per unit depth of penetration.

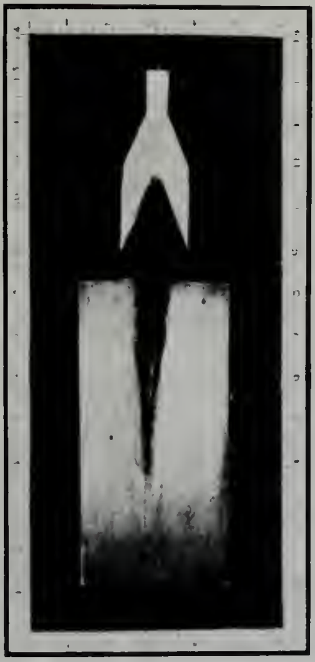


Fig. 14. Photograph of a solid steel cylinder (3.25 in. in diameter, 7 in. in length) which has been shot and then sawed in half to show the nature of the hole produced. A cross-sectioned replica of the charge that produced this hole is shown in the position that the real charge occupied before it was detonated. The real charge contained 0.25 lb. of Pentolite. The cavity liner was a steel cone (0.025 in. thick, 1.63-in. base diameter). (2)

Fig. 15. Photograph of a solid lead cylinder (4 in. in diameter, 9.5 in. in length) which has been treated the same as the steel cylinder in Fig. 3. The steel slug from the liner can be seen embedded in the lead about 5 in. from the bottom of the cylinder. (2)

The diameter of the jet itself is usually very small and considerably smaller than the hole formed. This has been determined photographically. Experiments have also been conducted in which the jet was made to pass through a 6-mm. hole in a screen without injuring it although the hole which the jet punched in a steel plate lying behind it had a diameter of 25-mm. (15)

As shown in Figs. 14-16, the hole diameters are smaller in hard materials than in soft, since more work must be done to open the hole in the harder materials. In soft materials, like lead, large diameter holes are produced because the radial momentum of the target material spreads it outward until it can be stopped by elastic or viscous forces.

Fig. 16. Photograph of a stack of alternate steel and lead plates after attack by a conical, lined charge. All plates were originally the same size, the top plate being of steel. This provides a striking demonstration that radial plastic flow produced by the jet is arrested more quickly by high yield strength materials (steel) than by low yield strength materials (lead). (2)

On the other hand, with most charges, the rate of penetration and the depth of penetration into most target materials are nearly independent of the strength of the target material. This arises from the fact that because of the high velocities of shaped charge jets, the pressures produced at the point of impact are far above the yield point of most materials. To a first approximation, the strengths and viscosities of target materials can

be neglected, and the problem can be treated by hydrodynamics.

PENETRATION WITH CONSTANT JETS

The theory presented in this section was discovered independently by R. Hill, N. F. Mott, and D. C. Pack in England; earlier similar semiquantitative ideas had been advanced by Kistiakowsky, Messerly, and Pugh. It is taken almost in its entirety from the Journal of Applied Physics of June 1948. (2)

In order to simplify the mathematical treatment by the elimination of several variables, the theory of penetration is first shown for the case of a constant jet. A constant jet is merely an idealized jet, as shown in Fig. 17a; it is assumed to have a constant length, ℓ, velocity, V, and density, ρ_j, and to be penetrating a semi-infinite target of density, ρ, with a velocity, U, as shown in Fig. 17b. A constant jet is assumed to be completely formed and in possession of the above-mentioned physical properties before it arrives at the target.

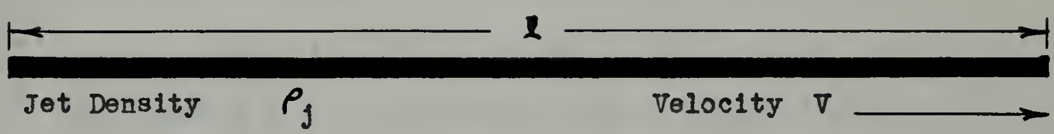


Fig. 17a. Idealized jet of length ℓ, velocity V, density ρ_j, and cross-sectional area A.

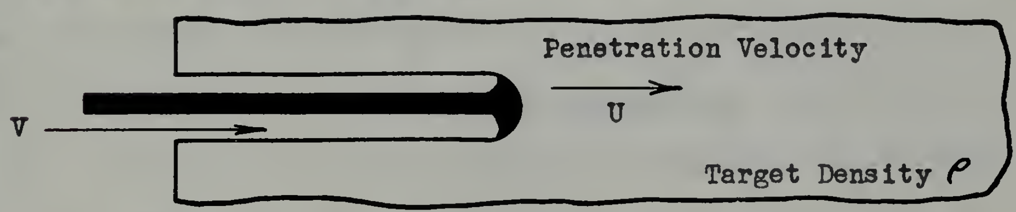


Fig. 17b. Idealized jet penetrating target material of density ρ, with a velocity U. Inasmuch as it is a continuous jet, it spreads out as it reaches the target.

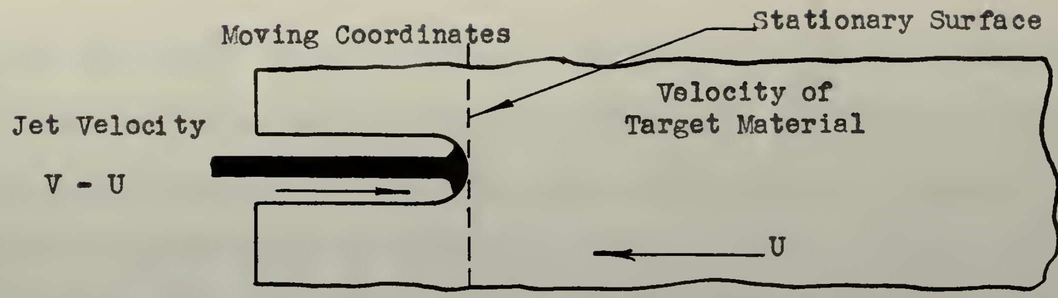


Fig. 17c. The steady state in (b) transferred to a coordinate system moving at the penetration velocity U. In this moving system the hole contour is fixed. (2)

Consider the case in which U has reached a constant value. The phenomenon is simplest when viewed in a system of coordinates moving with a velocity U, as shown in Fig. 17c. In this system, the hole profile is fixed, and the jet moves to the right at a velocity V-U, while the target moves to the left at a velocity U. If the pressure produced by the jet is large compared to the strengths of both the target and the jet material, they can be treated like perfect fluids. The pressure on the two sides of the surface of contact between the jet and the target must be the same. Hence, by Bernoulli's theorem, which is valid since the phenomenon is stationary in the coordinates we have chosen,

$$1/2 \quad \rho_j \, (V-U)^2 = 1/2 \; \rho \; U^2 \qquad (5)$$

The velocity U has been measured for a number of charges and target materials. Using lined, conical charges, the velocity U in steel targets has been observed to be as high as 2.7×10^5 cm/sec. In these cases, the pressure produced by the jet is $1/2 \rho U^2 = 0.5 \times 7.8(2.7 \times 10^5)^2 = 2.8 \times 10^{11}$ dynes/cm² or <u>0.28-million atmospheres</u>. Since this tremendous pressure is far above the yield strength of any steel, the treating of steel as a perfect fluid is justifiable.

The mechanism of penetration is illustrated in Fig. 17, which shows

the jet being used up by impinging on the target. If it is assumed that the steady state is reached almost instantaneously and that the penetration stops as soon as the last jet particle has struck the target, then the total penetration P is equal to

$$P = Ut_f = Ul/(V-U) = l\,(\rho_j/\rho)^{1/2} \qquad (6)$$

from Eq. (5), where l is the original length of the jet and t_f is the time of penetration.

This is a surprising result. It indicates that the depth of penetration into a massive target depends only on the length and density of the jet and the density of the target, but not upon the jet velocity. The lack of dependence on jet velocity is at first most surprising. However, one need only notice that although from Eq. (5) the velocity of penetration U is proportional to the jet velocity V, the rate at which the jet is used up is also proportional to V. Thus, a faster jet is used up in a shorter time, and the total penetration remains the same. Of course, this independence of the depth of penetration on the jet velocity can hold only for velocities great enough to produce pressures far above the yield strength of the target materials.

It is probable that after the last jet particle strikes a relatively soft target material it will have sufficient residual momentum to open up the hole still deeper. This effect has been called "secondary penetration" to distinguish it from that given by Eq. (6). It helps explain why deeper holes are produced in massive lead targets than in massive steel targets even though the lead targets have higher densities.

In jets from conical liners, a small amount of jet material at the rear of each jet travels slow enough to produce stresses lower than

the yield strength in armor, though higher than the yield strength in mild steel. Thus the penetration process may continue longer in mild steel than in armor. This phenomenon, together with the phenomenon of secondary penetration, accounts for the fact that the total penetration into steel armor is a little less than the total penetration into mild steel, and that the penetration into lead is greater than the total penetration into either of the steels.

Equation (6) indicates that the depth of penetration by a given charge should be inversely proportional to the square root of the density of that target. This is roughly true in many cases, though there are a number of exceptions, as evidenced in the previous paragraph, indicating that this simple model needs to be modified.

Though this theory correctly predicts a number of experimental phenomena, there are many experiments that show the inadequacy of this simple jet model. The average penetration into a given target at first increases and then decreases as the distance (standoff) between the charge and the target is increased. This phenomenon is illustrated in Fig. 18 by shots into a massive mild-steel target with a lined, conical charge.

A number of tests have been conducted in which the massive mild-steel target was part of a ballistic pendulum so that the momentum of the jet could be measured simultaneously with the penetration it produced. These experiments showed that while the average penetration varied greatly with standoff, the average momentum was almost constant and independent of standoff.

This result agrees well with present theory, which indicates that the penetration should be independent of the velocity of the jet. Further

confirmation of this point is found in Fig. 19, where the individual momentums of jets at a given standoff are plotted against the penetration they produced at this same standoff. The variations in momentums are smaller than those in penetrations, but the two variations show absolutely no correlation. Jets having the largest momentums did not produce the deepest penetrations.

If the material in the jet is broken up into very fine particles which are sufficiently separated so that they do not interfere with each

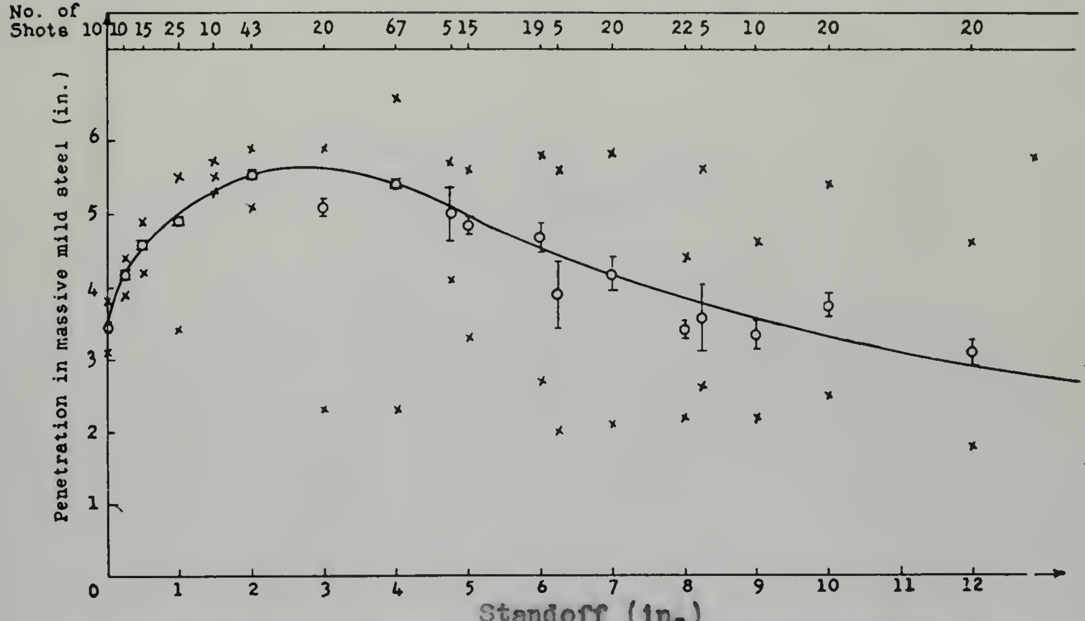


Fig. 18. Curves of average penetration into mild steel as a function of standoff. ⧲ indicates average penetration with the average deviation of the mean. X indicates the maximum and the minimum penetrations. (2)

other, the pressure produced by the jet will be greater than that indicated by Bernoulli's theorem in Eq. (5). This follows from the fact that a particle jet does not spread out over so large an area as a continuous one. The continuous jet is capable of supporting internal pressure, whereas the particle jet is not. This ability to support internal pressure produces a gradient in pressure along the axis of the jet with the highest

pressure at the point of impact with the target and reducing down to zero in the unaffected part of the jet. The gradient in the pressure causes a gradient of the opposite sign in the velocities within the jet from U at the point of impact with the target to V in the unaffected part. Since with a jet under steady-state conditions, the product velocity times cross-sectional area must be the same at all points, the gradient in the velocity causes the cross-sectional area of the jet to

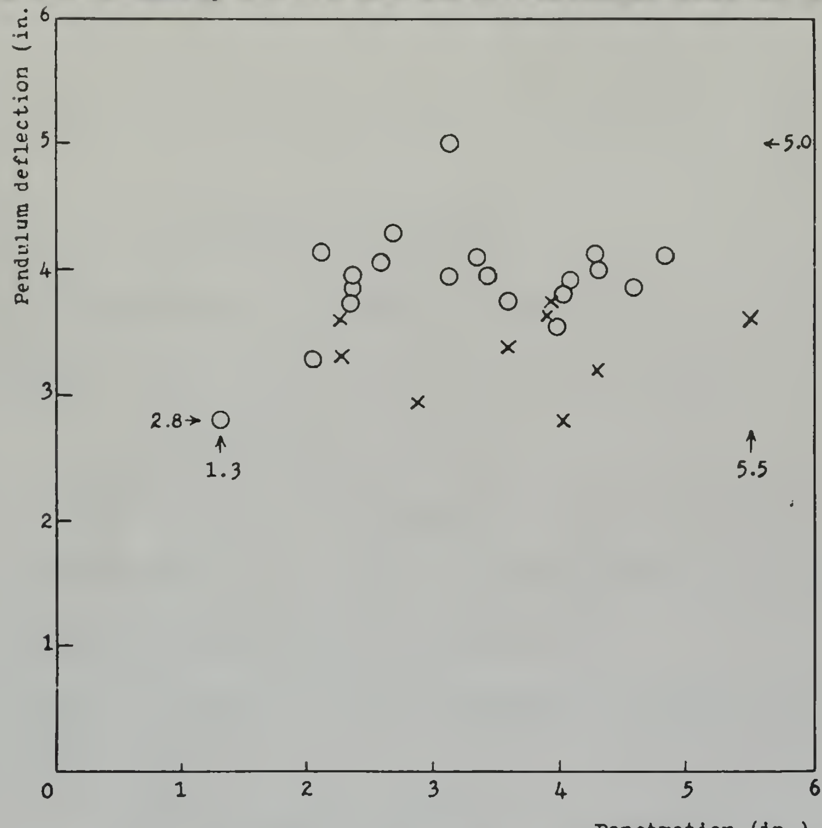


Fig. 19. Ballistic pendulum deflections versus penetrations into mild steel for standard charges at 12-in. standoff. The circles represent data obtained from one batch of charges, while the crosses represent data obtained from another batch. These charges were made to be identical, and no variations were observed before detonation. The second batch of charges gave nearly the same average penetrations as the first, even though their average jet momentums were lower. (2)

increase as it approaches the target.

With a particle jet of the kind assumed, the particles retain their velocity and area until they make inelastic impacts with the target surface and no such spreading takes place. The pressure produced by a particle jet can be calculated approximately by dividing the total force required to effect the change in momentum of the jet by the total area A the jet strikes. The total force is given by the rate of change of momentum $\rho_j A\ (V-U)^2$, and so the average pressure on the surface is $\rho_j (V-U)^2$. If this pressure is set equal to the pressure in the target material at the point of impact, as given by Bernoulli's equation (1'), we get

$$\rho_j\ (V-U)^2 = 1/2\ \rho\ U^2 \qquad (7)$$

This equation differs from (5) only by the factor 1/2 on the left side of the equation. The two Eqs. (5) and (7) can be combined into one

$$\lambda\ \rho_j\ (V-U)^2 = \rho\ U^2 \qquad (8)$$

where λ is a constant that equals <u>one</u> for continuous jets, and <u>two</u> for dispersed particle jets. If a jet is intermediate between these two types, λ may take values between one and two.

From Eq. (8), the penetration produced by either type of jet can be calculated

$$P = \ell(\lambda\ \rho_j/\rho)^{1/2}. \qquad (9)$$

This equation should hold only for idealized jets whose properties remain constant throughout the penetration process. Real jets show a more complex behavior which will now be discussed.

<u>PENETRATION WITH VARIABLE JETS</u>

Jets from conical liners are not constant idealized jets, but change in length, velocity, and density as they travel. For these <u>real</u>

jets, Eq. (9) must be modified. As mentioned earlier, the jet velocity decreases continually from the front to the rear; hence the jet becomes longer and longer. The increasing length produces other changes in jet characteristics that must be considered. Furthermore, real jets do not have the same properties throughout their length at any given time, and they are usually not completely formed at the time they start penetrating a target. This last raises the question as to whether or not the target may react upon the jet to change its characteristics while it is being formed.

Such a reaction of the target upon the formation of the jet cannot take place if the velocity of sound in the jet material is low enough so that any pressure pulse produced by the target cannot travel back to the neighborhood of the stagnation point (Fig. 11) in the jet being formed. This condition is generally realized even at low standoffs, since the velocities in the front part of the jet are higher, and those at the rear are not much lower than the velocity of sound in the jet material. With conical charges such as shown in Fig. 14, the conditions are such that no effect upon the formation of the jets can be expected from steel targets that are no closer to the charge than 1/2 inch. This is fortunate, for it makes it possible to divorce the process of penetration by jets from the process of formation of the jets.

To calculate the penetration of a jet into a target, one needs to know its physical characteristics at all points in the jet and at every instant of time. The true conditions are undoubtedly very complex. However, in calculating the penetration attributable to a jet, we need only concern ourselves with the average density, ρ_j, and state of dispersion, characterized by λ, of that part of the jet that is about to

strike the target at the given instant of time. The average density, ρ_j, is defined as the mass in a small section of the jet divided by the over-all volume of that section. It will be considered equal to the density of the liner material in continuous jets and lower than that in particle jets. The factor λ will be considered as a function of ρ_j, although it may also vary somewhat with the size of the particles into which the jet is broken. Let us assume that the ρ_j and λ, of that part of the jet from a given charge that is striking the target at the given instant, are independent of time and depend only upon the distance from the base of the original cone to the point where the jet is striking the target.

While this assumption is made because it greatly simplifies the calculations, it is probably close to the truth as any other simple assumption that could be made. If we neglect the relatively small compressibility of the metal in the liner, all parts of the jet from a given charge must leave the stagnation point (Fig. 11) with the same density. If the jet breaks into particles because it has a large velocity gradient, it is probable that the front breaks up first and the rear later, and thus the breaking may take place at approximately the same position in space for all parts of the jet. The subsequent reduction in density of the jet produced by spreading of the particles due to the velocity gradient and other causes is probably dependent more upon the distance that particular section of the jet has traveled from its point of formation than upon its position in the jet or upon the time since the process started.

It should be noticed that, while the theory of formation of jets from conical liners of uniform thickness indicates that the rear of each

jet should have more mass per unit length than the front, there is no reason to suppose that the densities at these points will be different. The jet cross section is probably larger at the rear than at the front, but this should not affect the depth of penetration, though it should affect the diameter of the hole produced.

With this assumption, since λ depends upon ρ_j, the ρ_j and the λ of that part of the jet from a given charge that is striking the target depend upon the distance x from the cone base but not upon the time t.

The penetration is given by

$$P = \int U dt,$$

where the integral is evaluated over the time of penetration. Now $d\ell = (V-U)dt$, where $d\ell$ is the small element of the jet that will strike the target and thus be removed from the jet in the next instant of time dt. Hence, neglecting transient effects,

$$P = \int U d\ell/(V-U) \tag{10}$$

integrated over the total length of the jet as it strikes the target. Assuming that Eq. (8) holds approximately for variable jets, Eq. (10) may be written

$$P = \int(\lambda \rho_j/\rho)^{1/2} d\ell \tag{11}$$

or

$$P = 1/(\rho)^{1/2} \int (\lambda \rho_j)^{1/2} d\ell \tag{12}$$

if the target is of constant density. The integral in Eq. (12) depends primarily on the jet characteristics, so that penetrations of similar charges into different targets should be inversely proportional to the square root of the density of the target just the same as for constant

jets. However, Eq. (12) predicts that the penetration into a given target by a given variable jet will depend upon the distance between the charge and the target, whereas the penetration with constant jets would be independent of this distance.

Let the standoff s be the distance between the original cone base and the surface of the target. Since the jet lengthens as it travels, the integral in Eq. (12) for a given jet depends upon s. An exact calculation of this dependence is difficult and is hardly justified, considering the uncertainty in the original assumptions. However, an excellent idea of this dependence can be obtained by the use of some approximations.

Eq. (12) may be written as

$$P = \bar{J}/(\rho)^{1/2} \int d\ell$$

where $\bar{J}$ is a kind of average value of the quantity $(\lambda \rho_j)^{1/2}$ during the process of penetration. Its value lies somewhere between the values of $(\lambda \rho_j)^{1/2}$ at the beginning and at the end of the penetration. According to our assumption that λ and ρ_j for a given charge depend on distance but not on time, $\bar{J}$ depends primarily on s. The quantity $\bar{J}$ and the integral $\int d\ell$ both depend very slightly upon the density ρ of the target, since a different penetration in a different density target will change the average obtained for $(\lambda \rho_j)^{1/2}$ as well as the value of $\int d\ell$. For both, the dependence upon ρ is so slight it will be neglected. The integral $\int d\ell$ for a given charge also depends primarily on s. If the jet were of constant length, $\int d\ell$ would give this length, since it represents an integration of all the elementary lengths of jet as they strike the target. With a variable length jet, $\int d\ell$ represents an effective length,

for it is the sum of all of those elementary lengths of the jet that at each instant are causing the penetration. This effective length $\int d\mathfrak{l} = \mathfrak{I}$ depends primarily upon s. Equation (12) becomes

$$P = \overline{J}\,\mathfrak{I}/(\rho)^{\frac{1}{2}} \qquad (13)$$

From Eq. (13) the approximate dependence of P on s can be calculated. There are three cases to consider, all of which may occur at different stages in the same jet.

Case 1. - The jet is "drawn out" like a ductile metal and becomes narrower. The jet density ρ_j is unchanged, and, since λ is a constant equal to one for a continuous jet, P increases in direct proportion to $\mathfrak{I}$. The process of ductile drawing of the jet due to the velocity gradient in it was first suggested because the increase in penetration proportional to $(\mathfrak{I})^{\frac{1}{2}}$ for particle jets of Case 3 did not appear to be rapid enough to account for the experimental observations.

Case 2. - The jet is in the process of changing from the first (continuous) to the second (particle) type of jet. It has broken up into particles, but the particles are still so close together that on impact with the target, the jet acts almost as though it were continuous. The value of λ is intermediate between 1 and 2, but approaches 2 in an unknown manner as the jet lengthens. Thus λ increases and ρ_j decreases with standoff. Whether $\overline{J}$, the average of $(\lambda\rho_j)^{\frac{1}{2}}$, increases, decreases, or stays constant depends upon whether λ increases faster than, slower than, or at the same rate as ρ_j decreases. Some experiments suggest that $\overline{J}$ first increases slightly, and then decreases with increasing standoff. Probably the penetration produced is much the same as that of Case 1, where $\overline{J}$ is constant and the penetration is proportional to $\overline{I}$.

Case 3. - The jet consists of finely divided particles with unchanging cross-section. The factor λ is a constant equal to 2. Since the decrease in ρ_j is caused by the lengthening of the jet due to its velocity gradient, the average value of ρ_j should be inversely proportional to $\mathcal{I}$, and $\bar{J}$ should be inversely proportional to $(\mathcal{I})^{\frac{1}{2}}$. Thus from Eq. (13), P should be proportional to $(\mathcal{I})^{\frac{1}{2}}$. The penetration increases with standoff, though at a slower rate than with jets of Cases 1 and 2.

The nature of jets from conical liners depends upon the physical properties of the cone materials under the conditions of temperature and pressure found in the jets. Probably all metallic jets pass through each of the three stages, starting out as continuous but sooner or later breaking up into particles. The metals that are less ductile under these conditions break up into particles sooner than those that are more ductile. Thus, charges with more ductile linings, like aluminum and copper, produce larger penetrations as the standoff increases than do those with less ductile linings. In each case, the penetrating ability increases with the standoff of the charge from the target, rapidly at first during the ductile drawing and more slowly after the jet has broken up into particles.

It might seem that the penetrating power of these jets should increase indefinitely, but there are a number of reasons why this does not happen, the more important of which are given below:

1. In practice, the jets are never perfectly aligned, so they tend to spread and their effective density is reduced, thus reducing their penetrating ability.

2. The reduction in jet density caused by both lengthening and

spreading eventually reduces the pressures produced in the targets until their strengths can no longer be neglected, and the simple theory breaks down.

3. At great distances, the particles spread so far apart that the air resistance on the individual particles becomes an important factor. Close to the charge (within 10 or 15 times the diameter of the base of the cone) air can be treated approximately like any other target having the same density. The front of the jet creates a very intense shock wave with an evacuated space behind it which reduces the air resistance on the rest of the particles in the jet to a negligible quantity.

All of the above tend to reduce the penetration as the standoff increases.

EFFECT OF STANDOFF ON PENETRATION

An approximate expression for the penetration as a function of the standoff s can be obtained for variable jets from Eq. (13). However, it is necessary to neglect any changes in velocity because of forces acting upon each jet particle from the time the jet is formed to the time when the particle strikes the target. This approximation is not serious because the forces acting upon the jet particles in this period are relatively small. The internal forces acting during the ductile drawing process change the velocities somewhat but not enough to seriously affect the rate at which the length of the jet changes, which is the quantity that now concerns us.

The effective length, $\bar{l}$, of the jet increases linearly with standoff, s, because of the gradient of velocity which is known to be approxi-

mately constant along the jet. The ratio of the effective length at standoff s to that at s = 0 is then roughly

$$1 + \alpha s,$$

where α is a constant depending upon the velocity gradient.

For particle jets, the effective density $\bar{\rho}_j$ of the jet depends upon its effective length, $\bar{L}$, and its effective cross-sectional area. The effective cross-sectional area increases with standoff because of spreading. If there are no appreciable forces upon the jet particles, they will travel in straight lines, and the radial spreading will be linear with s. If the radial spreading is symmetrical about the axis, the ratio of the effective jet radius at standoff s to that at s = 0 is roughly

$$1 + \beta s$$

where β is a constant that determines the rate of spreading. The ratio of the effective cross-sectional area at standoff s to that at s = 0 is

$$(1 + \beta s)^2$$

if the spreading is symmetrical. If the spreading is somewhat non-symmetrical, this relation holds less exactly.

Although the actual jet density is constant in the continuous jet of Case 1, the effective jet density may decrease with standoff because of waver caused by faulty alignment. For lack of better information, it may be assumed that the continuous jets waver through the same solid angle as the particle jets spread. The ratio of effective jet density due to spreading or wavering at standoff s to that at s = 0 is roughly

$$1/(1 + \beta s)^2.$$

The penetration of these jets can then be obtained approximately

from Eq. (13). For Cases 1 and 2

$$P = P_0 (1 + \alpha s)/(1 + \beta s) \qquad (14)$$

where P_0 is the penetration at $s = 0$.

For particle jets of Case 3, for which $\lambda = 2$, the penetration is approximately

$$P = P_0' \left[\sqrt{2}(1 + \alpha s)^{\frac{1}{2}} /(1 + \beta s) \right], \qquad (15)$$

where P_0' is the value for P from Eq. (14) at the value of $s = s_1$ where the jet breaks into particles. Generally each jet passes through the stages described by Case 1, Case 2, and Case 3 in that succession.

Curves of penetration versus standoff can be fitted very well with Eqs. (14) and (15), using values of α, β, and s_1 that other experiments have shown to be reasonable. However, they generally cannot be fitted with Eq. (15) alone. At low standoff the experimental penetration rises so rapidly with standoff that some ductile drawing needs to be postulated to account for the facts.

EXPERIMENTAL VERIFICATION

Equation (8) indicates that the velocity of penetration U should depend upon the density of the target material ρ but should be independent of all other properties of the target. Since Eq. (8) was derived for steady-state conditions like those shown in Fig. 17c, it cannot be strictly true for variable jets. However, it should hold approximately for average values of V and U if the velocity measurements are made over a distance so short that the jet properties vary only slightly during the process. To compare results with different targets, it will be necessary to have all of the targets at the same distance from the

standard charge so that the average density of the penetrating jet is, as nearly as possible, the same in each target.

A number of different target materials, in plates of 2-in. thickness, have been tested at 6-in. standoff from standard charges with conical steel liners (base diameter 1.63 in., apex angle 45°, wall thickness 0.036 in.). A high speed rotating drum camera was used to record the speed of the jet just before and just after it perforated the target plates (V_b and V_a, respectively) and the time required for that perforation. Striking examples of the excellent work being conducted along these lines are shown in Figs. 21 and 22. These microsecond photographs were taken at Carnegie Institute of Technology where comprehensive research on jet action is being done for Army Ordnance under the direction of Dr. Emerson Pugh. The average velocity $\bar{U}$ is obtained from the perforation time, and the average jet velocity in the target is given by $(V_b + V_a)/2$. Eq. (8) can now be written

$$\frac{V - U}{U} = (\rho / \rho_j \lambda)^{\frac{1}{2}} = (\rho)^{\frac{1}{2}} / J,$$

or

$$\frac{V}{U} = \left[(\rho)^{\frac{1}{2}} / J \right] + 1, \qquad (16)$$

where $J = (\lambda \rho_j)^{\frac{1}{2}}$ depends only on the jet density for a given liner material.

From Eq. (16) a straight line should be expected if the ratio of average velocities $(V_b + V_a)/2\bar{U}$ is plotted as a function of $(\rho)^{\frac{1}{2}}$, where ρ is the target density. Figure 20 shows such a plot.

From the slope of the line in Fig. 20, the average value of $\lambda \rho_j$ (reciprocal of the square of the slope) of these jets, when they are between 6 and 8 in. from the cone base, can be obtained. The average,

maximum, and minimum values of $\lambda \rho_j$ from Fig. 20 are, respectively, 3.0, 9.0, and 1.4 g/cc. If λ is near 2 in each case, the jet densities are, respectively, 1.5, 4.5, and 0.7 g./cc., which should be compared with 7.8 g/cc, the density of steel. The value 4.5 g/cc for the best jet is so near the density of steel that this jet probably acted somewhat like a continuous jet with a λ less than 2. In which case, the actual density was more than 4.5 g./cc.

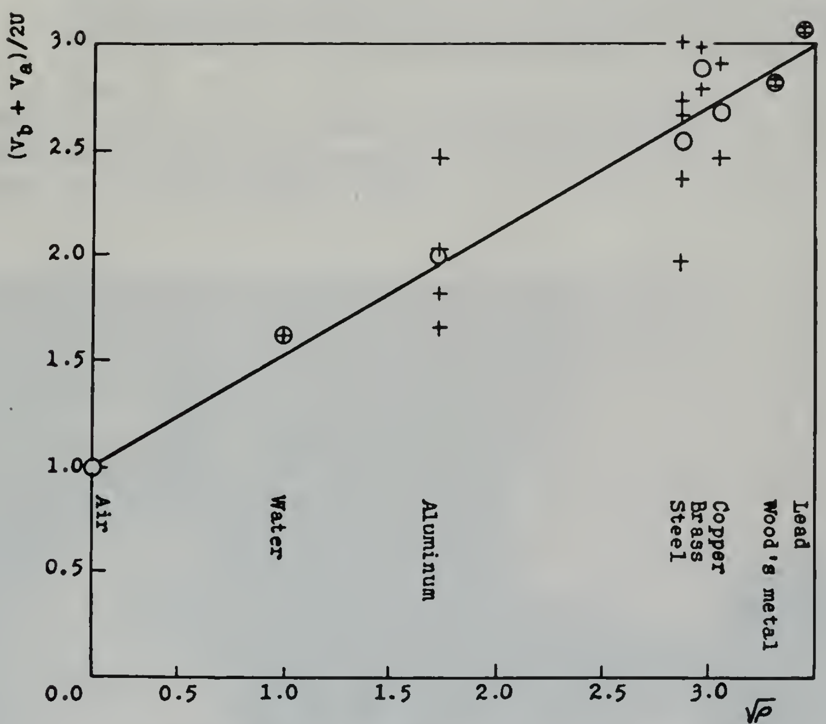


Fig. 20. The ratio for standard charges of the average jet velocity to the average penetration velocity in material of different densities. The crosses indicate the averages for each material. (2)

Fig. 21. Jet emerging through a section of armor plate makes neat bulge and glows brilliantly because of air friction caused by its tremendous speed, which is about 10 times that of a rifle bullet. (50)

Fig. 22. In photo taken at a millionth of a second, a shaped charge hits a section of half-inch armor plate from the left and sends a steel jet (thin horizontal line) through to the right. (50)

SUMMARY

1. With constant jets, the depth of penetration into a massive target depends only on the length and density of the jet, and on the density of the target, but not upon the jet velocity. However, this independence on the jet velocity holds only for velocities great enough to produce pressures far above the yield strength of the target material.

2. With constant jets, the depth of penetration by a given charge is theoretically inversely proportional to the square root of the density of the target material. This is roughly true in most cases. However, it should be realized that the penetration process will continue longer in materials of low yield strength than in those of high yield strength, as the slower, trailing portion of the jet may be able to produce stresses greater than those of lower yield strength materials; whereas it might be stopped by higher yield strength materials.

3. The average penetration into a given target at first increases and then decreases as the standoff is increased from zero standoff.

4. The nature of jets from conical liners depends upon the physical properties of the liner material. It is believed that all metallic jets probably start out as continuous, but sooner or later break up into particles.

5. Brittle materials perform more poorly than ductile materials. If optimum performance is to be obtained with a brittle material, it should be fired at a shorter standoff than would be required for a more ductile material of equal density.

CHAPTER IV

FACTORS AFFECTING PENETRATION

Some degree of the Munroe effect may be obtained with any kind of high explosive by cutting a cavity of almost any size or shape in the side of the charge that is to face the object to be attacked. As has been mentioned before, demolition engineers sometimes cut a small "chunk" out of a block of dynamite before placing it against an object to be severed. Miners have even been known to arrange sticks of dynamite in the shape of a teepee to blow a hole in the ground. Munroe himself constructed the first practical shaped charge by tying sticks of dynamite around and on top of a tin can, thus creating a cylindrical cavity in the middle of the charge.

However, to attain the full benefit of the Munroe effect, certain factors must be taken into consideration in the design of the charge and in its fabrication.

As is frequently the case with new discoveries, widespread application of shaped charges preceded a complete understanding of the theory. World War II saw a race between United Nations and Axis experts to learn more about the best ways to determine optimum values for such variables as standoff, wall thickness, strength of explosive, cone angle, etc. This entailed a great deal of experimentation. However, by dint of much research, there evolved a wide variety of shaped charges which could be counted on to produce definite results, and these saw considerable service during World War II.

Since a shaped charge is primarily a penetration device, the depth of penetration is generally used as the criterion of its efficiency.

This is expressed as the maximum thickness of the target just perforated by the jet (generally in steel, or concrete), or the depth the jet will penetrate into a target too thick to be perforated. The latter method appears to be more widely used.

The design of a shaped charge is complicated by the intricate interdependence of several obvious factors in addition to certain less obvious ones. In most applications, the design for maximum jet efficiency must be a compromise of these several factors which will now be discussed.

STANDOFF

Standoff is the term used to define the distance in air between the base of the shaped charge and the target. This space is necessary to allow a more or less complete formation of the jet before it strikes the target, and any hindering material (such as water, oil, sand, etc.) will markedly reduce penetration. In shaped charges with conical liners, standoff for optimum performance increases with increasing apex angle. The optimum standoff for similar liners of different materials may vary over a considerable range. Optimum valves of standoff generally range between 1 to 3 times the diameter of the liner base of a conical charge. The average standoff employed in four U. S. statically fired charges is 1.40 times the diameter of the base. The average standoff employed in six U. S. projectile-type charges is 2.33 times the base diameter. This figure was obtained from drawings, and does not indicate what the effective standoff is at the time of detonation.

Standoffs for military shaped charge weapons which are fired at their target are expressed as the length of the hollow space below the

liner base in front of the shaped charge shell, grenade, rocket, etc. The resultant standoff is less than that shown in a drawing because of the partial crushing of the hollow nose before the fuse functions. This effect must be taken into consideration in the design of the weapon.

The average depth of penetration into a given target at first increases and then decreases as the standoff is increased. This phenomenon is illustrated by Fig. 18 of Chapter III.

SYMMETRY

Symmetry of the charge about a central axis (or central plane in the case of linear charges) is of utmost importance. This should include geometrical and metallurgical uniformity of the liner, physical and chemical uniformity of the explosive, and symmetry of detonation.

A burr, crack or slight unevenness in the cone or its lining may result in more resistance to the explosive force on one side of the cone than on the other and hence may cause the jet to wobble and lose part of its effectiveness.

Liners must be free from internal defects as well as being geometrically symmetrical. However, annealing is no longer considered worthwhile for obtaining good performance.

GEOMETRY, MATERIAL AND THICKNESS OF LINER

Many different geometrical shapes of liners have been tried, e.g., cones, hemispheres, paraboloids, pear shapes, trumpet shapes, etc., however, none has appeared to provide remarkable advantages over any of the others. Conical liners appear to give the deepest penetrations and are encountered most frequently. Hemispherical liners are used when large

hole diameters are desired. Symmetry of shape rather than type of shape is the important factor.

Many different types of liner materials have been tried. The following have been used to varying extents in shaped charges: copper, mild steel, cast iron, aluminum, aluminum alloys, zinc, brass, tin, lead, and glass. For deep penetration of solid targets, copper liners give maximum performance, with liners of mild steel and high copper alloys giving good results. Glass and aluminum liners produce large hole diameters but shallower penetrations. Application, cost, and ease of manufacture are important considerations in liner choice. Glass liners are preferred in charges employed for drilling shot holes for they form easily pulverized slugs which can be raked from jet holes leaving them cool and safe for the insertion of secondary explosives.

Most work in this country has been done with conical liners of uniform wall thickness and having apex angles of 30° to 60°. Tests have been conducted by Clark (7) to determine the importance of wall thickness and tapered walls. Tapered-wall cones of increasing thickness from apex to base were found to give somewhat higher values of penetration than uniform wall cones. However, the concensus of opinion today is that the slight increase in penetration obtained by tapered cones is not of sufficient value to justify their use, in view of their higher cost and difficulty of manufacture.

In cones of uniform wall thickness, tests show that penetration varies considerably with variation in wall thickness. The thinner the wall, the greater the jet velocity. For cones of the same apex angle, the optimum wall thickness is proportional to the base diameter. Optimum wall thickness also increases as the apex angle is increased. Hence it is

seen that optimum wall thickness for conical liners is dependent upon apex angle as well as the base diameter of the charge.

TYPE OF EXPLOSIVE

While it was shown earlier that surprisingly enough, the depth of penetration is not dependent upon the jet velocity, it must also be remembered that this independence holds only as long as the jet velocity is great enough to produce pressures far above the yield strength of the target material. Since the jet velocity is directly proportional to the velocity of detonation, it follows that only those explosives which possess a sufficiently high rate of detonation, with the exception of aluminized explosives, are applicable for use in shaped charges.

Tests were conducted by G. B. Clark (7) in the summer of 1946 with three kinds of explosives to determine the approximate relationship between velocity of detonation (which he assumed to be roughly proportional to the explosive strength) and penetration effect. While only a few shots were fired with rather widely scattered results (Table I), it was indicated that the relationship is approximately linear, although for a given increase in velocity of detonation, say, doubling it, the penetration is not doubled, but is increased by some factor that is less than one times the velocity of detonation. Clark stated that more complete tests may show that the curve of penetration vs. velocity of detonation is an exponential one.

The preferred explosive is one of high density and high brisance which will reach its maximum velocity very rapidly, such as is found in pressed or cast solid organic nitrates or nitrocompounds, or high density

blends of more than one such compound.

Shot No.	Number of Plates	Depth of Hole, In.	Diameter of Hole, In.
45% Gelamite; Velocity of Det., 8,500 Ft. per Second			
1	9	2-1/2	1-1/4
2	5	1-1/4	1-1/4
3	5	1-1/4	1-1/4
Av.	6-1/3		
60% N. G. Dynamite; Velocity of Det., 19,000 FPS			
1	5+	1-3/8	2
2	11+	2-7/8	2
3	8+	2-1/8	1-7/8
Av.	8		
100% Oilwell Explosive; Velocity of Det., 26,000 FPS			
1	10	2-1/2	2
2	dud		
3	16+	4+	1-1/2
4	15-1/2	3-7/8	1-3/4
5	9+	2-3/8	1-3/4
Av.	12.8		

TABLE I - Penetration of three kinds of explosives in steel plates using two-inch hemispherical charges with cast aluminum cases, aluminum-alloy liners, and three-inch standoff. (7)

No one explosive can be said to be the best for all applications. Compressed pentaerythritol tetranitrate (PETN) is a suitable material, or compressed or cast blends of this compound with trinitrotoluene, for example, in 50/50 mixtures (Pentolite). Likewise, trimethylene trinitramine (Cyclonite) is a suitable explosive, as are its high density mixtures with TNT.

Those rated among the best by the U. S. Navy are the castable

explosives, Composition B, Pentolite, and PTX - 2. For extemporized field charges, the plastic explosive, Composition C-3, gives good results.

Various other detonating explosives, however, are well adapted for use. High strength commercial dynamites may also be used, but are less adapted in many ways than the solid organic explosives.

The following factors, when present, will definitely influence the final choice of explosive:

(1) Force of setback, if the charge is to be employed in a launched missile.

(2) Operating temperature.

In industrial applications, cost of the explosive is generally an important item.

The following tabulation showing various types of explosives employed by various nations in shaped charge weapons may be of interest to personnel engaged in their design. It should be understood that this list is by no means complete, and that it represents only those explosives which have come to the attention of the author during the course of this study. The order of listing of explosives has no significance.

PROJECTILES

UNITED STATES

(a) 50/50 Pentolite

GERMANY

(a) TNT

(b) Cyclonite/Wax/TNT

(c) Cyclonite/Wax (95/5) pressed in blocks wrapped in waxed paper

(d) Cyclonite/Wax (60/40) pressed in blocks wrapped in waxed paper

JAPAN

(a) Cast mixture of 60% TNT and 40% Cyclonite wrapped in varnished paper

ITALY

(a) TNT

(b) 58% Cyclonite, 40.5% TNT, 1.5% Wax

(c) Tritolite (50% TNT/ 50% Cyclonite)

<u>ROCKETS</u>

UNITED STATES

(a) 50/50 Pentolite

GERMANY

(a) Cyclotol

<u>GRENADES</u>

UNITED STATES

(a) 50/50 Pentolite

GERMANY

(a) Cast TNT

(b) Dinitroaniline with TNT

(c) Cyclonite/Wax

(d) Cyclonite/TNT (60/40) Blocks wrapped in waxed paper, wrapping cemented to interior wall of casing

JAPAN

(a) 50/50 Pentolite, wrapped in waxed paper

(b) RDX/TNT (50/50)

BOMBS

GERMANY

(a) Amatol, 50/50 or 60/40

(b) TNT

(c) TNT/RDX (46/54)

JAPAN

(a) RDX/TNT (50/50) - (TANOYAKU)

(b) 70% TNT/ 30% HND

ITALY

(a) RDX/TNT/Wax (60/38/2)

MINES

GERMANY

(a) TNT

(b) RDX/TNT

JAPAN

(a) Crude TNT

DEMOLITION CHARGES

UNITED STATES

(a) 50/50 Pentolite

(b) 82/18 Comp. B/50-50 Pentolite (booster)

(c) 94/6 " " " "

BRITAIN

(a) PETN/TNT (25/75)

HEIGHT AND WIDTH OF EXPLOSIVE

The effect of charge height on performance has been investigated by Lewis and Clark. (25) The most effective height of charge above the

apex appears to be a little over two charge diameters for 45° cones. Increasing the height of charge beyond 2 to 3 diameters has little effect on the penetration. Expressed in a different manner, the length of the explosive charge from the lowest point where the explosive contacts the liner to the point of initiation should be as great as possible up to a maximum of 3 or 4 charge diameters.

With regard to explosive width, optimum performance is obtained when the diameter of the explosive is equal to or only slightly greater than the diameter of the liner. (62) Increasing the explosive diameter beyond the diameter of the liner actually tends to decrease performance in some cases.

CONFINEMENT OF EXPLOSIVE

Tests have been conducted by G. B. Clark (7) to determine the effect of confinement of the explosive (other than that offered by the liner). Eight shots were fired on granodiorite using conical charges of 100% blasting gelatin with 60° cast iron cones, 3 inches in diameter. The cases were made of molybdenum steel and their thickness was increased successively from 1/4 inch to 3 inches. The results are shown in Table II.

Shot No.	Thickness of Case, In.	Spall, In.	Hole Depth, In.	Total Depth, In.	Diameter of Hole, In.
1	1/4	3-1/2	4	7-1/2	1
2	1/4	2	3	5	1
3	1/2	3	4	7	1-1/2
4	1/2	2	7	9	1-1/2
5	1	2	8	10	2
6	2	1	8	9	3
7	2	2	8	10	3
8	3	3	7	10	3

TABLE II - Effect of confinement of charge in cast-steel cases on penetration in solid granodiorite. (3-in., 60° cast-iron cones; 100% blasting gelatin). (7)

The increase in hole diameter and volume is significant and can be attributed directly to the effect of confinement. The increase in penetration was appreciable, though perhaps not as great as expected. There was approximately a 60% increase in penetration in going from a 1/4-in. case to a 3-in. case. The accompanying increase in cost and weight of the case, however, would hardly be justifiable. It is interesting to note that the increase in penetration between a 1/4-in. and 1/2-in. case is approximately 28% which is more in the practicable range.

In the case of military weapons, degree of confinement is often determined by other factors, particularly in projectiles where ballistic factors must be taken into consideration.

Clark has suggested that the mechanics of the confinement effect are probably threefold:

"(1) The action of rebounding gas molecules from the inside surface of the case has an effect on more complete and perfect detonation of the explosive, and ensuring propa-

gation of the high velocity of detonation of 100% blasting gelatin;

"(2) much more of the force of the explosion itself is directed toward the point of least resistance, the cavity end of the charge. This has a result of

"(3) more of the explosive force being directed against the cavity liner itself to give a stronger jet."

ROTATION

It has been found that if a shaped charge is rotated at a high rate of spin, say 10,000 r.p.m., such as is obtained with artillery projectiles, the effect of penetration is greatly reduced. A static penetration figure of 3 to 4 calibers is reduced in shaped charge, armor-piercing projectiles to 1-1/2 to 2 calibers for this reason.

As the rate of projectile spin is increased from 0 to about 12,000 r.p.m., penetration by a conical, lined charge decreases to about 50% of its static value, after which further spin has little additional detrimental effect.

Although hemispherical liners show less degradation due to rotation, their penetration is less than that of conical liners. For this reason, conical liners are used in most applications where penetration is the prime factor.

METHOD OF INITIATION

In beehive type charges, optimum performance is obtained when the wave front is perfectly symmetrical with respect to the liner. This is obtained when the charge is initiated from a point on its axis of symmetry and on the side farthest away from the base of the charge.

In the case of high speed projectiles, rapid initiation is important. The use of percussion type nose fuses incorporating a small shaped charge which upon impact initiates a booster at the rear of the charge is becoming more widespread as its action is faster than the functioning of a base fuse.

In the case of linear cutting charges, most effective results are obtained when the charge is initiated from an end.

SCALING LAWS (62)

For maximum performance with conical liners of a given base diameter, optimum liner thickness and optimum standoff increase with increasing angle of liner.

With conical charges, penetration increases directly as the base diameter. This linear scaling law has been found to be so general that it has been used to a great extent. As a result, other quantitative shaped charge data are usually given as percentages of this diameter.

CHAPTER V

MILITARY APPLICATIONS

The shaped charge as a military weapon saw its advent in World War II during which it rapidly grew to maturity. The Munroe effect was for some time the secret within many secret weapons and it achieved spectacular results in anti-tank defense and in the destruction of pillboxes and similar heavy concrete fortifications.

The true lethal effect of a shaped charge weapon can hardly be gauged by the size of the hole it punches in a target. Rather is the damage caused by:

(1) the spray of hot, high speed metal fragments from the jet and those spalled from the back of the target which ricochet throughout a target interior,

(2) the jet penetrating and detonating munitions,

(3) the jet or hot fragments setting fire to combustibles,

(4) the hot gases, blast effect, and flying debris tending to make life unendurable for the occupants.

In addition, the charge container explodes into lethal fragments on the outside of the target; however, any damage resulting from these must be considered of a purely secondary nature.

With the relaxation of security restrictions many of the military uses of shaped charges have been widely publicized in such well known magazines as Popular Science, Life, and The Illustrated London News, and in various trade journals and newspapers.

During World War II, the development of shaped charges in this

country was carried on under the cognizance of the Joint Army-Navy N.D.R.C. Shaped Charge Committee. This work is currently being continued under the auspices of the Department of Defense.

One of the most important features of the shaped charge from the military standpoint is that the penetrating effect is independent of the speed with which the weapon arrives at the target. Statically-fired charges as a matter of fact, are usually more effective than those moving at high speeds. This has been particularly useful from the standpoint of hand-placed charges and also of rocket projectiles which, because of their relatively slow speeds, could not be expected to penetrate heavy fortifications if conventional armor-piercing heads were employed.

The shaped charge has permitted the foot soldier to rise to new stature for he is now able to match the devastating effect of light and heavy artillery by means of weapons which he can carry in his hands or on his back.

This chapter will present a general description, including limited design details, of typical shaped charge munitions, both foreign and domestic, many of which saw service during World War II. In view of the fact that many of our own shaped charge weapons and current developments in this field are generally of a confidential nature, they are of necessity omitted from this work.

The foreign munitions described are largely those of the defeated Axis powers, information concerning which was largely obtained from captured weapons and by our occupational teams after the cessation of hostilities.

PROJECTILES

Prior to the use of the shaped charge principle in projectile construction, increased penetration using conventional AP projectiles was obtained largely by increasing the striking velocity. This led to the development of high-velocity guns, in which field the Germans made tremendous strides with Sabot-type projectiles and so-called "squeezebores." These of course, are still important from the standpoint of obtaining high muzzle velocities for increased ranges and shorter times of flight.

Shaped charge projectiles have the advantage of giving good armor piercing characteristics to low velocity projectiles. For example, the U. S. 75-mm Anti-tank Shell M66, when fired from the 75-mm howitzer with a muzzle velocity of 1000 feet per second will penetrate 3.6 inches of armor. Since the penetration is independent of striking velocity, this penetration is applicable at any range up to the limit of the howitzer.

By comparison, a standard AP shell fired from a 75-mm gun with a muzzle velocity of 2030 feet per second will penetrate 3.1 inches of homogeneous plate at 1000 yards. This penetration will fall off at increased ranges as a result of decreased velocity of the shell due to air resistance.

It should be borne in mind, however, that if the AP projectile is able to pass through a target before detonating, the lethal effect may be much greater than in the case of a shaped charge projectile which detonates on the outside and only the jet penetrates the target.

High rotational speeds such as are experienced by projectiles

fired from most rifled weapons cause a decided reduction in the penetrating power of shaped charges. For example, proving ground tests show that when a U. S. 105-mm shell is fired with a muzzle velocity of 1250 feet per second it will penetrate 4.7 inches of armor. When detonated statically, however, it will penetrate 8 to 10 inches of the same armor. (62) By comparison, the performance figures for the 100-mm German H1/C Hollow Charge Projectile against homogeneous armor are: static - 155 mm (6.1 inches), dynamic - 100-mm (3.94 in.). (58) Overcoming the loss of efficiency at high rotational speeds presents one of the main problems in the future of shaped charge development.

Although hemispherical liners show less degradation due to rotation, their penetration is less than that of conical liners, and hence practically all U. S. projectiles have conical liners. This of course is influenced by the desired result. The Germans on the other hand have made wider use of hemispherical charges in the past.

It is also interesting to note that practically without exception, German artillery projectiles and some other foreign makes are fuzed with impact nose fuzes. In addition a long central flash tube generally extends part or all of the way from the gaine (booster) which is located at the base of the shell to the nose fuze. This causes the detonating force of the nose fuze to be directed toward the base of the shell where the gaine subsequently initiates the main charge at the proper position for jet action.

In the United States, however, base detonating fuzes were used in the past with but one exception, this being in the 57-mm HEAT Shell, M307. This particular shell in 1947 was unique for two reasons. First, it was the only standardized shell in this country that contained a

hemispherical liner, and second, it was the only shaped charge shell to employ an instantaneous nose fuze. This fuze (M90) causes a small shaped charge jet to be shot down the central tube initiating the main booster charge. The hemispherical liner was used because it was believed to be less affected by rotation than a conical liner and also because the apex of the conical liner would be too close to the point of detonation in this small shell.

Shaped charge projectiles have been adapted to almost every conceivable weapon by foreign powers, the Germans having undoubtedly outsurpassed all others in this field. Shaped charge shells were designed by Germany during World War II for such pieces as tank cannon, anti-tank guns, assault guns, mountain guns, field guns, recoilless guns for airborne troops, infantry guns, howitzers, etc.

Germany also designed 75-mm shaped charge projectiles for Belgian, Jugoslav, French, and Dutch guns and a shell for the 76.2-mm Russian howitzer.

The Italians were also found to have equipped a large range of artillery weapons with hollow-charge ammunition. Of the types that have been recovered, all show a similarity of design in that they appear to be converted H.E. shells.

Typical shaped charge projectiles are shown in Figures 23, 24, 25, and 26.

ROCKETS

One type of shaped charge rocket used by the United States is the 2.36-inch high explosive anti-tank rocket. It is the ammunition for the famous "Bazooka" developed by the Army Ordnance Department.

Fig. 23. —Shell, HE, AT, 75-mm, M66. (62)
(United States)

Fig. 24. —Shell, HE, AT, 57-mm, M307. (62)
(United States)

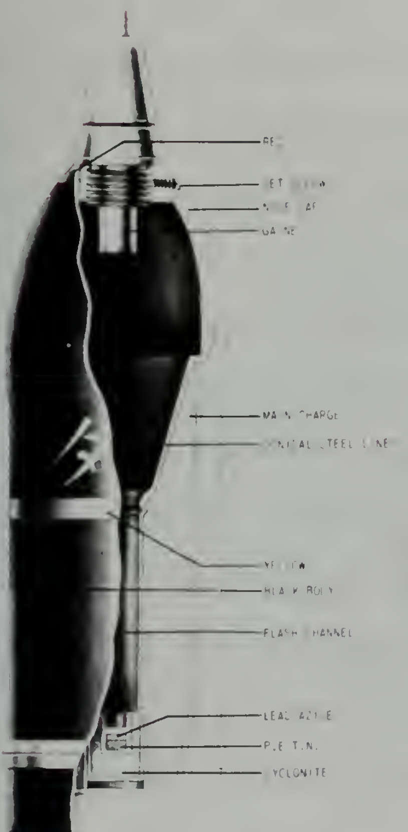


Fig. 25. Type 2 7-cm
Hollow-Charge Projectile. (60)
(Japanese)

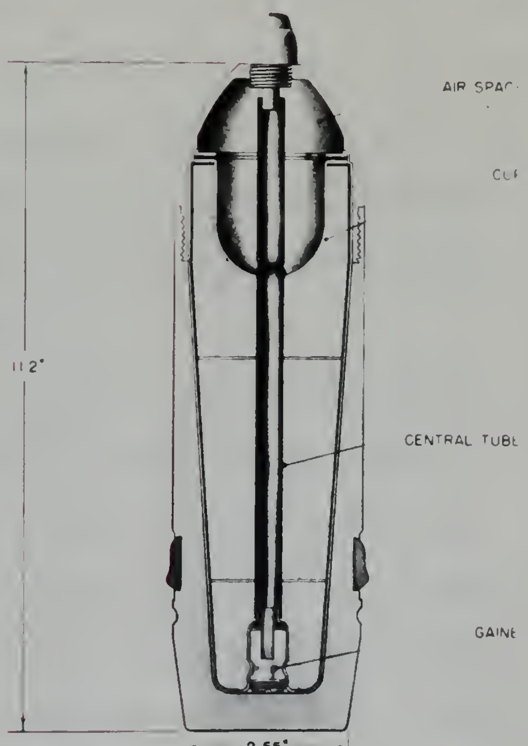


Fig. 26. Hollow Charge Projectile for Tank Gun, 75-mm, 7.5-cm Gr. Patr. 38 KwK. (H. L.) (58)
(German)

Originally designed as a grenade for the caliber .50 machine gun, it was lator fitted with a rocket motor and first saw service in the North African campaign where it won quick approval.

The earlier designs of this rocket have been constantly improved and a late model, the M6A5, is shown in Fig. 27.

Proving ground tests show that when fired at a velocity of 275 feet per second, this rocket can consistently penetrate 4-1/2 to 5 inches of armor plate with a 30° angle of impact. This is equivalent to a perpendicular penetration of 5-1/2 to 5-3/4 inches. Static tests of this rocket using a standoff of 1-1/2 inches give a penetration of 6 to 7 inches of armor plate. By comparison, the U. S. 75-mm (2.95 in.) anti-tank shaped charge projectile, M66, which was described earlier, when fired from a howitzer with a muzzle velocity of 1000 feet per second will penetrate only 3.6 inches of armor. The M66 has a 42° mild steel cone and has a 1 pound explosive charge of 50/50 pentolite. The 2.36-inch rocket is equipped with a 42° copper cone and is loaded with only 1/2 pound of the same explosive. These results are at first rather surprising and further emphasize the detrimental effect of high rotational velocities on shaped charge action.

During the early stages of the Korean War, it was discovered that the 2.36-inch bazooka was unable to cope with the thick armor plate of the Russian-made tanks. As a result, a heavier version of this weapon, the 3.5-inch anti-tank rocket was pushed into production and proved equal to the situation. Simultaneously, a 6.50-inch anti-tank aircraft rocket was rushed into manufacture and it proved to be a devastating tank killer. It is interesting to note that the time from its inception until the first complete round was manufactured was only

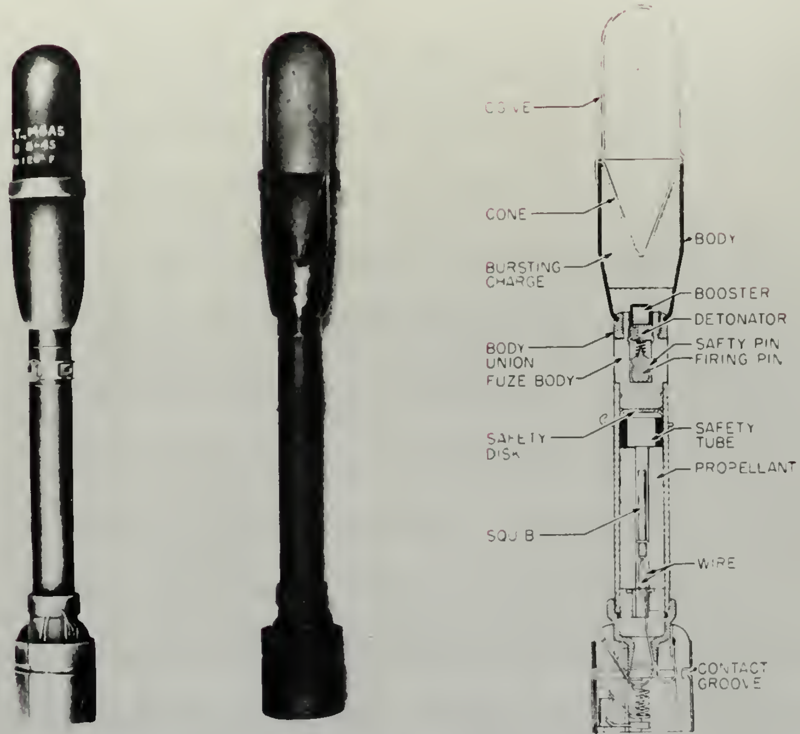


Fig. 27. —*Rocket, HE, AT, 2.36-inch, M6A5.* (62)
(United States)

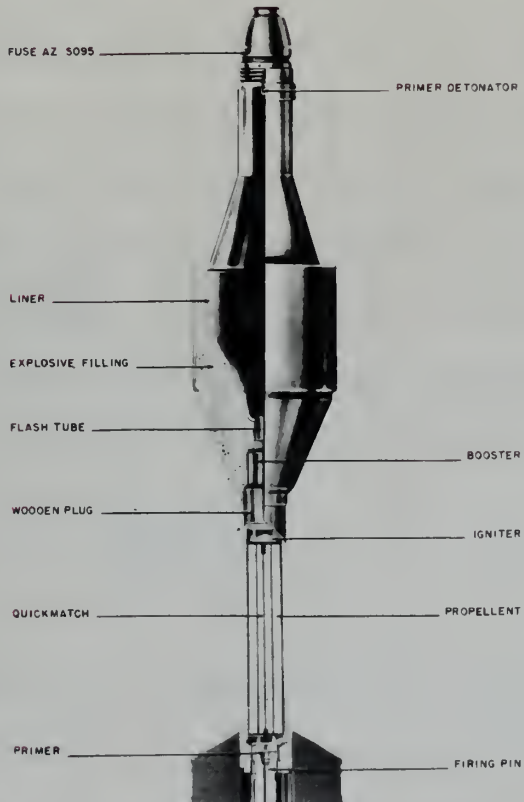


Fig. 28. —*8.8-cm Hollow Charge Antitank Rocket* (57)
(German)

two weeks. It should be emphasized that angle of impact is not as critical with shaped charge weapons as it is with AP shells, which factor is extremely important in anti-tank warfare.

On the foreign scene, the Germans had developed an 8.8-cm. (3.5-in.) H.E. hollow charge anti-tank rocket as shown in Fig. 28. This weapon was fin stabilized and was fired from a mobile anti-tank rocket launcher. It was equipped with a pear-shaped liner and an instantaneous nose percussion fuze. The charge consisted of 1.45 pounds of Cyclotol. No performance data is available for this weapon.

Another rocket weapon developed by the Germans was the Faustpatrone Hollow Charge Grenade. (57) This weapon was rather unique in that it was launched from a simple 31-1/2 in. metal tube which was then discarded. The tube contained a propellant charge in a waxed cardboard container which was held in position by a set screw. The projector was equipped with a sight which was adjustable for the relatively short 33-yard range of the rocket. During firing, the tube was held under the right arm, the left arm supporting the forward part. On discharge, a sheet of flame up to 6 feet long came from the rear end of the tube. The grenade weighed 6.62 lbs., had a bursting charge of 3.4 lbs., and was equipped with 4 folding tail fins and a base fuze.

GRENADES

HAND GRENADES

The value of shaped charge hand grenades is a questionable issue. It appears that the few which have been designed were planned to be used primarily as anti-tank weapons. Some grenades of this type are designed to go off on impact. Others are equipped with delay elements and with

some means of fastening them to a target.

It should be realized that should a grenade of the latter type miss its mark and fall to the ground, there exists a good possibility that the base of the shaped charge may end up facing the thrower. Upon detonation, the jet will have a much greater lethal range than an ordinary grenade.

Fig. 29 shows a Japanese anti-tank hand grenade which was made in two sizes of weights 1.85 and 2.75 pounds. The smaller grenade had an aluminum conical liner; the other had a liner of steel. Tied around the top of the grenades was a 14-inch tail of hemp to provide stability in flight and to make the weapon strike base first. The fuze was designed to function on impact.

The Germans had several shaped charge hand grenades. Fig. 30 shows a 2.2 pound grenade designed for anti-tank use. This grenade was fitted with four folding canvas fins which flew out when thrown giving the grenade stability. The liner was of odd design, being partially conical and partially hemispherical. Detonation occurred on impact.

Fig. 31 shows a German magnetic anti-tank hand grenade. It was a relatively heavy weapon, weighing 7 pounds 11 ounces and was fitted with three pairs of magnets which were sufficiently powerful to cause it to adhere to a vertical surface. This grenade was equipped with two delay-type igniters of 4-1/2 and 7 seconds, and is reported to have penetrated as much as 4.33 inches. The cone angle was 60°. It is doubtful that this grenade was intended to be thrown very far, if at all. Another similar weapon was called the Panzerhandmine 3 which is discussed in this work in the section on Mines.

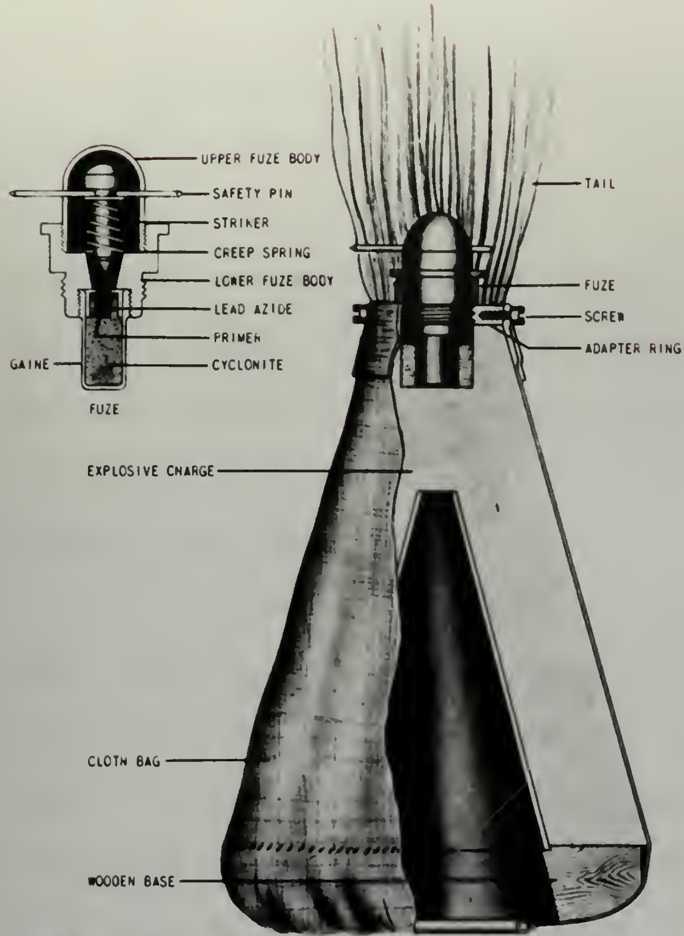


Fig. 29. —*Type 3 Conical Antitank Hand Grenade.* (59) (Japanese)

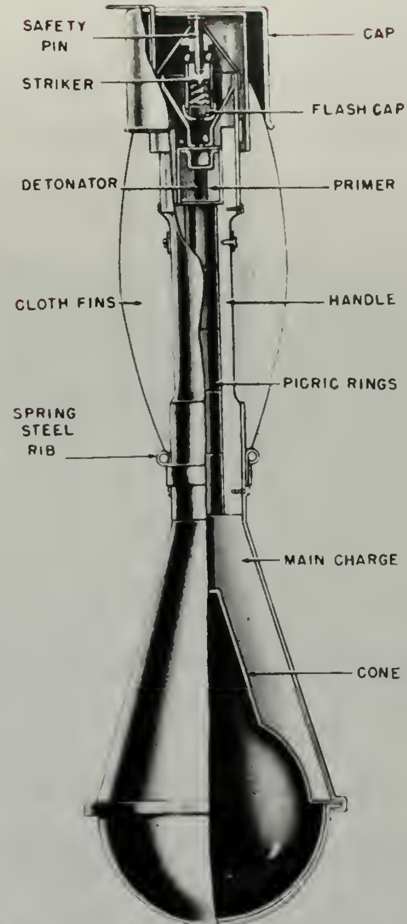


Fig. 30. —*Panzerwurfmine Hallow Charge Hand Grenade* (57) (German)

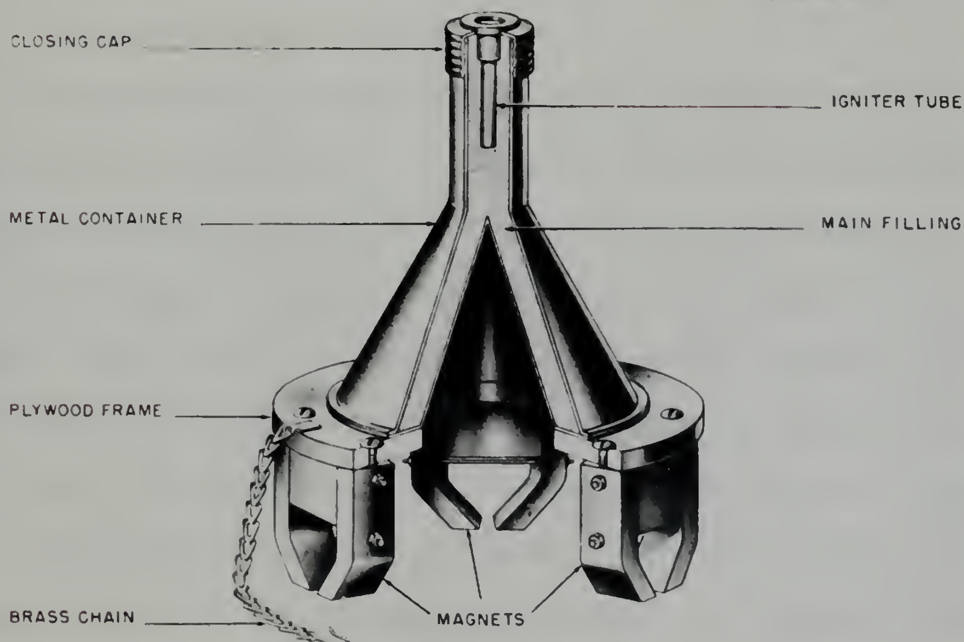


Fig. 31. —*Magnetic Antitank Hand Grenade* (57) (German)

The Germans had still a third type of shaped charge grenade called the "sticky type." The base of this grenade had a flat sticky pad which was covered during transit with a press-on lid. No information is available as to whether this grenade was thrown or placed against the target. It is possible that it could be lobbed for short distances, although this would have been very difficult as it had no means for stabilization.

RIFLE AND PISTOL GRENADES

The anti-tank rifle grenade, M9, has the distinction of being the first shaped charge weapon to be placed in service by United States forces. An improved model, the M9A1, is shown in Fig. 32. This weapon has a range of 365 yards with the standard grenade cartridge, and greater ranges with an auxiliary cartridge. A grenade launcher must be attached to the rifle before use of the grenade.

The M9A1 has a 1/4-lb. charge of 50/50 Pentolite and is equipped with a 44° conical mild steel liner.

Firing tests have shown that the M9A1 will penetrate 3-1/2-inch armor plate 80% of the time at an angle of 23°, with average entrance and exit hole diameters of 0,65 and 0.18 inches respectively.

The Japanese had at least two sizes of shaped charge rifle grenades. The larger was a 40-mm grenade having a total weight of 12.45 ounces and a charge of 3.81 ounces of 50/50 RDX and TNT. This weapon had a conical liner and base detonating fuse, and was a copy of the German Gross Gewehr Panzergranate. It was fired from a cup launcher attached to the standard 6.5-mm rifle, the propelling charge consisting of a special cartridge with a wooden bullet.

The other size was a 30-mm grenade which was similar to the one just described, except that it had a total weight of 8.25 ounces and a charge weighing 1.75 ounces.

Germany had several sizes and types of anti-tank, shaped charge, rifle grenades ranging from 8.8 ounces to 15-1/2 ounces. All had conical liners except one which had a hemispherical liner. The grenade stems had a prerifled section to correspond with the rifling of the discharger cup. Detonation was initiated by base detonating fuzes. Little information is available as to the ranges of these weapons. An 8.8-ounce grenade had a range of 50 yards while the 13-1/2-ounce weapon shown in Fig. 33 had a range of 100 yards.

A somewhat different type of hollow charge rifle grenade possessed by the Germans was the 37-mm H.E. anti-tank stick grenade, also called a rodded bomb for the 3.7 cm (1.45 in.)P.A.K. 41 gun. This was a heavy grenade weighing 18-3/4 lbs. and having a bursting charge of 5.3 lbs. of 60/40 Cyclonite/TNT. See Fig. 34. This grenade had a steel rod which fitted into the gun bore, and a concentric perforated sleeve which fitted around the barrel. Six fins provided stability in flight. This weapon was fitted with both nose and base fuzes.

The Germans also had a hollow charge pistol grenade weighing 1.3 lbs. designed for firing from the Walther 27-mm signal pistol.

BOMBS

Germany, Italy and Japan developed a limited number of shaped charge bombs during World War II though little information is available as to their use.

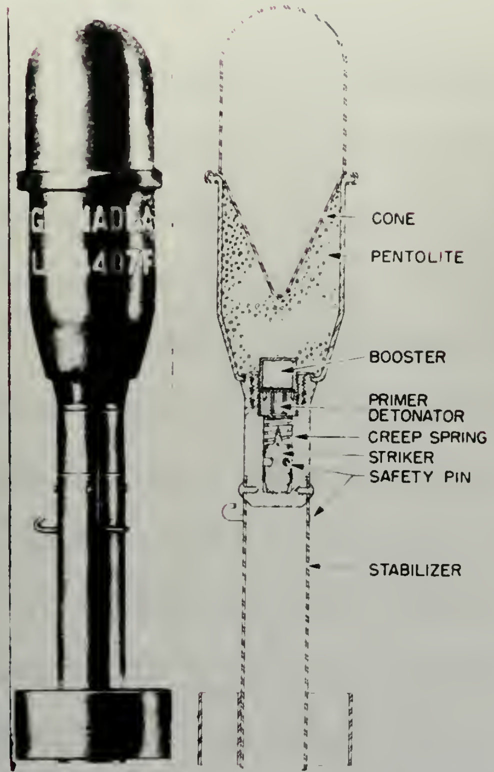


Fig. 32.—*Rifle Grenade, AT, M9A1.*(62)
(United States)

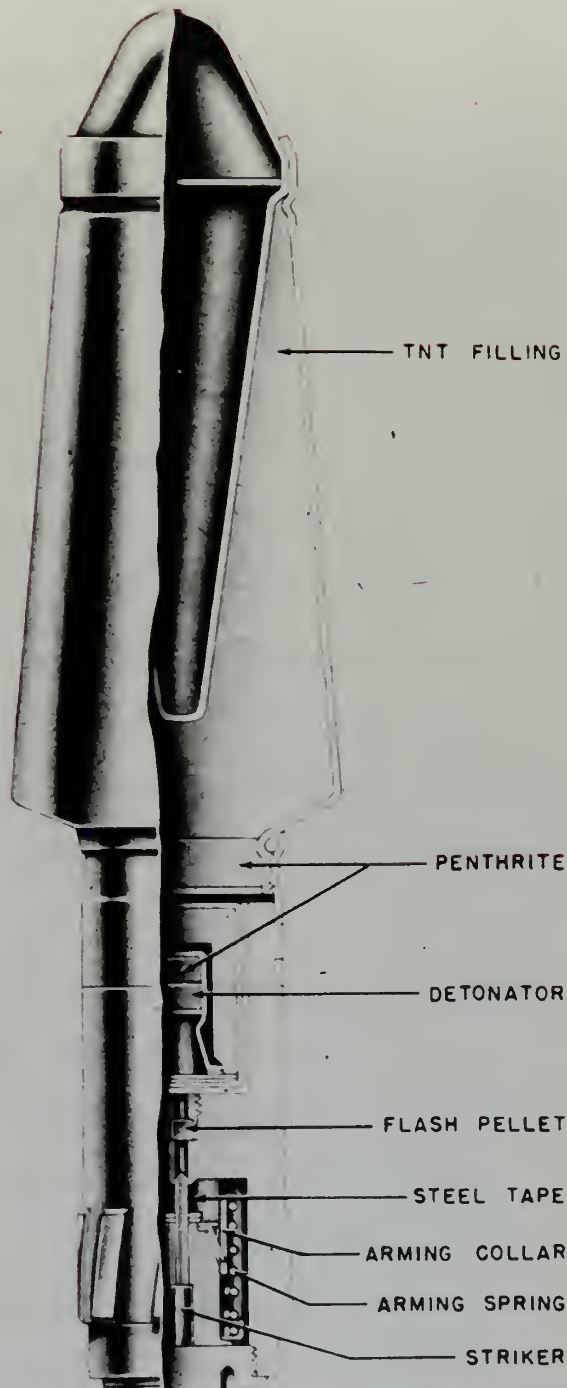


Fig. 33.—*Large Hollow Charge Rifle Grenade* (57)
(German)

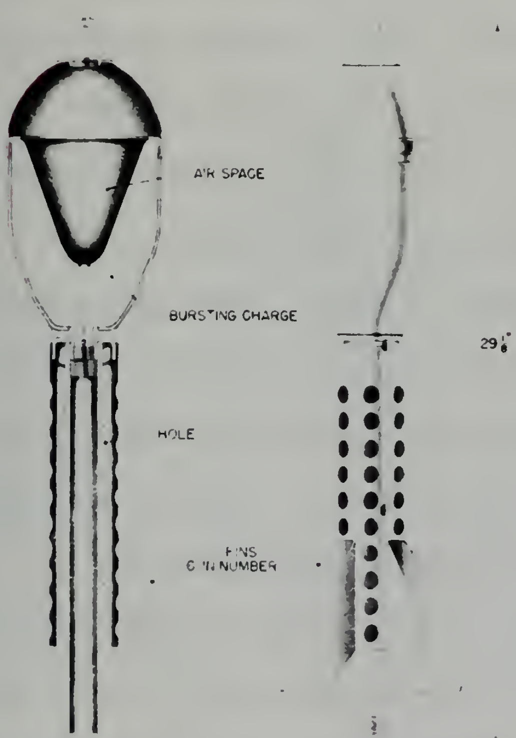


Fig. 34.—*Rodded Bomb for A. T. Gun 41, 37-mm, 3.7-cm Pak. 41* (58)
(German)

The Japanese developed small cluster bombs of 1/3-Kg and 1-Kg size. Captured documents describe the use of the former in air-to-air bombing in clusters of 30 or 76 per container. See Fig. 35. The later were carried in clusters of 40.

The Italians had designs completed for 3.5, 5, 25, 50 and 100-Kg hollow charge bombs although the 3.5-Kg was the only bomb of this type known to be used or manufactured by them. See Fig. 36. All of these bombs were similar in appearance, except the 25-Kg which differed slightly.

Germany had several types of shaped charge bombs as shown in Figs. 37 and 38. The SD 4-Kg HL Hollow Charge Bomb was designed as an anti-personnel and vehicle bomb. It employed a rather unique method of initiation. On impact, the Z66 nose fuse induced an electric current which passed via electric leads to the detonator in the base of the bomb where a squib was fired, setting off the gaine (booster) and the charge.

Details of the SD and HL type bombs were obtained from documentary evidence only.

The German 250 H.L. could penetrate 13.8 inches of armor plate. The 500 H.L. could penetrate 2 feet of armor plate or 11-1/2 feet of concrete. Performance figures for an 800 H.L. bomb are not available but it appears that with an H.E. charge of 110 Kg, it was hoped to penetrate 3.3 feet of armor or 19.7 feet of reinforced concrete.

The special nose device for use with SD 250 bombs consisted of a hollow charge which was to be attached to a bomb of standard type. This charge, which weighed about 4 Kg was detonated by its own fuse located in the nose of the device. In order that the detonation of the hollow charge would not damage the bomb, the space between the charge

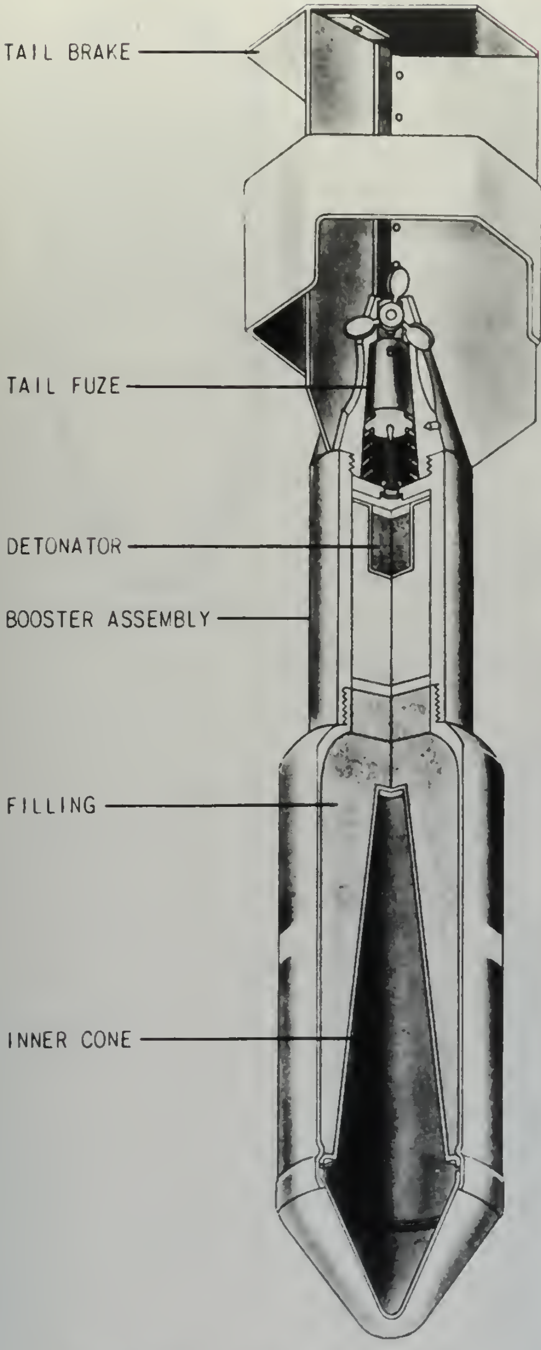


Fig. 35. Type 2 1/3-Kg Cluster Bomb. (59) (Japanese)

Fig. 36. – *Hollow-Charge Bombs* (21) (Italian)

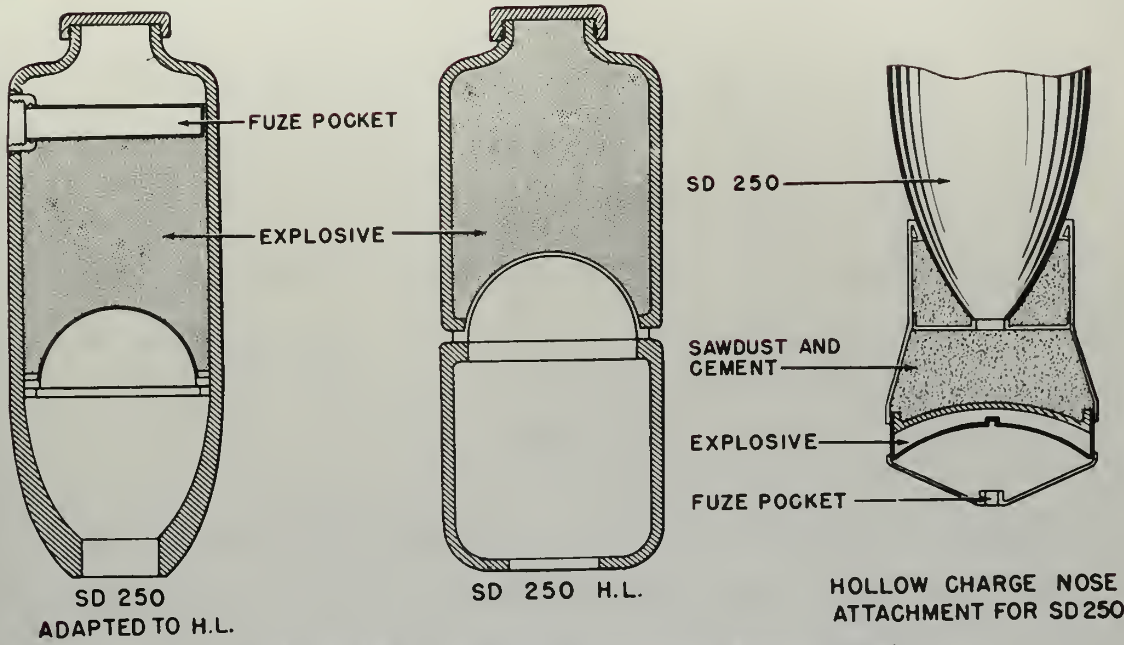


Fig. 37. —*SD and H.L. Hollow Charge Bombs* (57) (German)

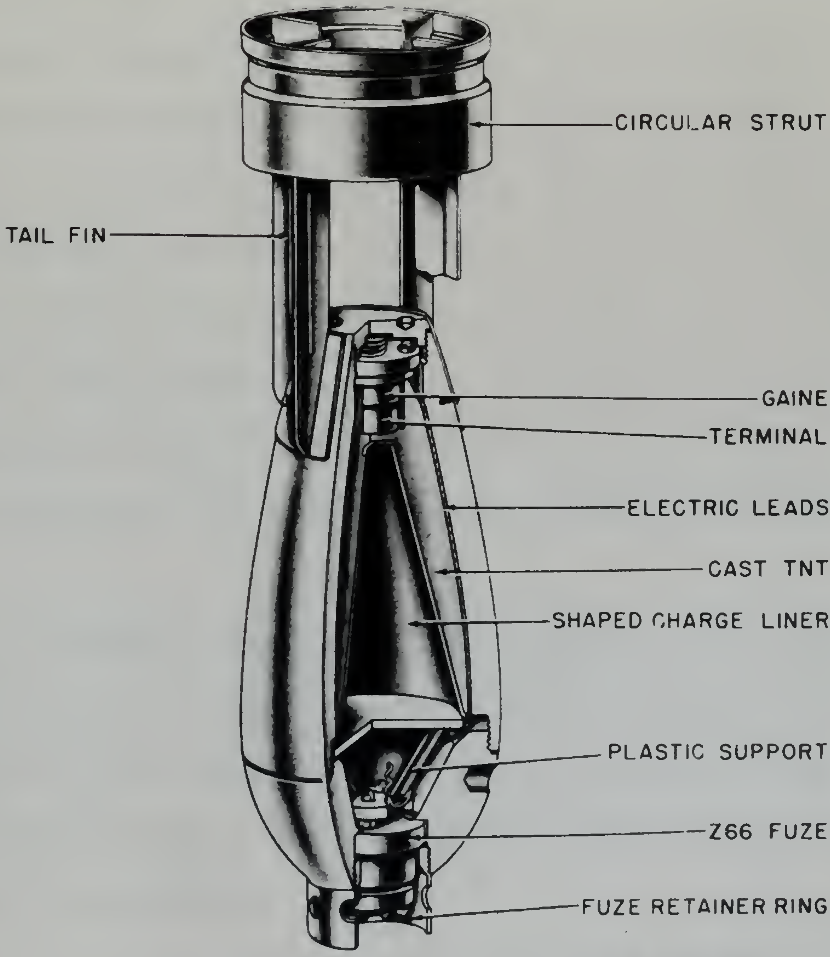


Fig. 38. —*SD 4-Kg HL Hollow Charge Bomb* (57) (German)

and the bomb was filled with a mixture of sawdust and cement. This special nose device for the SD 250 obtained greater penetrating power from low altitudes, the bomb following through the hole made by the nose piece. The bomb had a short delay fuze so that detonation would occur inside the target.

MINES

Nothing has been found in the literature regarding the application of the shaped charge principle to the more familiar types of mines such as sea mines, and land mines of the anti-tank, anti-vehicle, and anti-personnel types.

Two shaped charge weapons are included in this section principally because they are designated as mines in their nomenclature.

The first is the Japanese Lunge Mine which has been rather widely publicized in the open literature. As shown in Fig. 39, this weapon consisted of a conical charge attached to a long pole. It was designed for use against tanks; a charge of 6.6 lbs. of crude TNT made it capable of penetrating 6 inches of steel. Three metal legs 6 inches long and welded to the base of the charge container guaranteed the proper standoff.

This was strictly a suicide weapon. In practice, the operator pulled out the safety pin, then lunged at the tank in bayonet style. When the legs of the mine struck the target, the handle was driven forward breaking the shear wire, and the striker was driven into the detonator initiating the explosion.

Another mine-type weapon was the German magnetic anti-tank charge

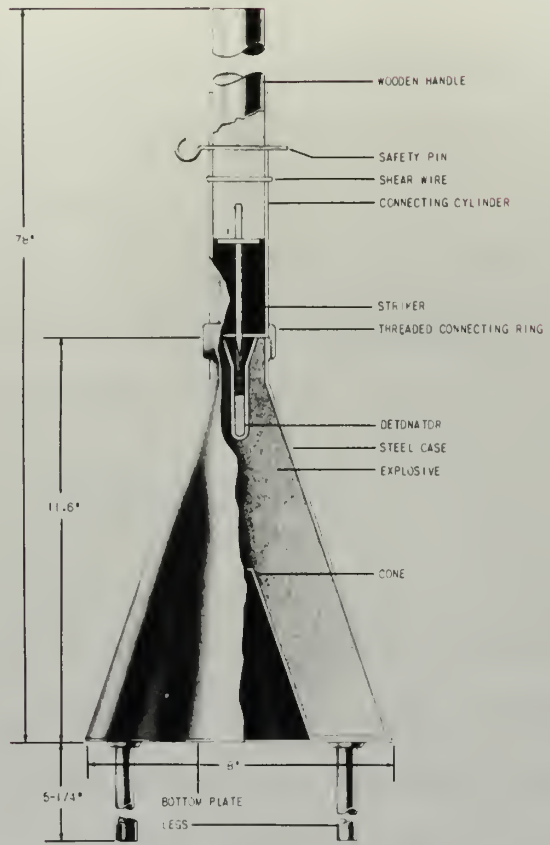


Fig. 39. —*Lunge Mine.* (59)
(Japanese)

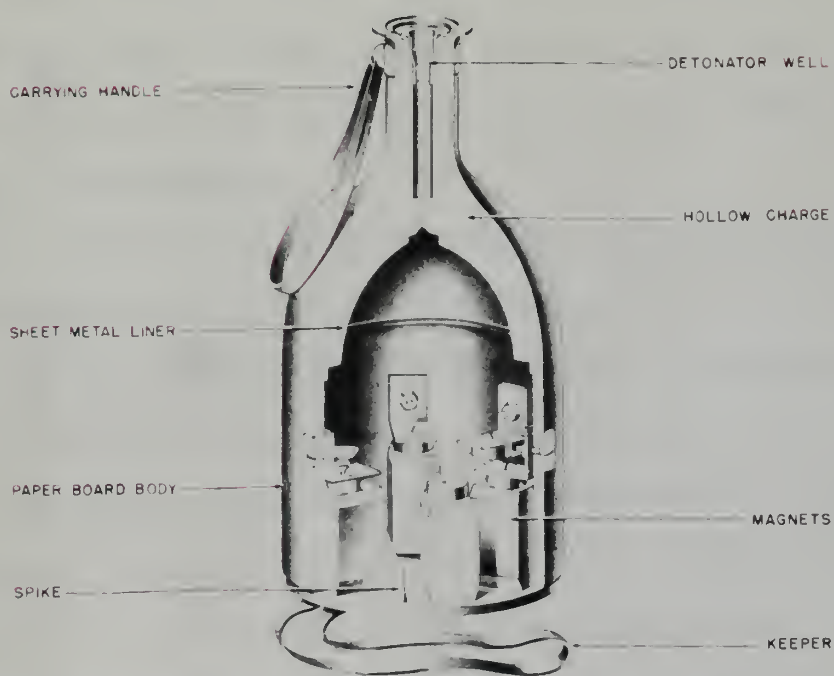


Fig. 40. —*Panzerhandmine 3 Antitank Magnetic Charge Mine* (57)
(German)

(Panzerhandmine 3) shown in Fig. 40. This was an 8-lb. assault weapon designed to be placed on enemy tanks or similar targets, to which it could adhere by means of magnets or spikes. The 2-1/3 lb. explosive charge was of TNT or RDX/TNT. The container was of paperboard and the iron keeper ring containing the spikes was reversible. The charge was fired with a 7-1/2-second friction igniter.

DEMOLITION CHARGES

Two very familiar beehive-type shaped charges which were designed for the penetration of armor and reinforced concrete are the U. S. Corps of Engineers 15-lb. M2A3 and the 40-lb. M3 shown in Figs. 41 and 42 respectively. These charges gave excellent results during World War II in punching bore-holes in masonry, concrete, or brickwork, and in the destruction of reinforced concrete pillboxes.

In bridge demolition, bore-holes may be quickly made in piers or abutments using shaped charges. These holes are then packed with a secondary explosive and on detonation will cause complete disruption and collapse of the structure.

The use of drilling machinery for making shot holes for blasting such as is frequently required during hasty withdrawals is usually impractical. The shaped charge, however, provides a satisfactory and rapid means of drilling these bore-holes. In order that the resulting hole may be filled with a secondary explosive material, it is essential that the hole not contain a hot metal slug, which is usually the case when a metal is used as the liner material. The M2A3 employs a high density <u>glass</u> cone primarily for this purpose. It forms an easily-

pulverized slug which can be raked from the jet hole leaving the hole relatively cool and safe for inserting secondary explosives. The glass cone has a further advantage of producing a hole with a greater volume (although slightly less depth) than a similar steel cone.

The M2A3 will penetrate armor plate to a depth of 12 inches, with a hole diameter tapering from approximately 3-1/2 inches to 2 inches. It will also penetrate reinforced concrete to a depth of 32 inches with hole diameter tapering from about 3-1/2 inches to 2 inches. The charge causes a small amount of cratering at the surface and considerable spalling at the back side. Against thicker targets, complete penetration can generally be obtained by firing successive charges over the same hole.

Because of a scarcity of Composition B when this charge was developed, 50/50 Pentolite was standardized as the filler. Charges manufactured toward the end of the war, however, contained the more powerful and cheaper Composition B.

Although this charge contains no metal parts (with the exception of the closing cap and detonator well), the case being of molded fiber, it is recommended that personnel be under cover and at least 100 yards away on detonation.

The 40-lb. M3 charge, unlike the M2A3, has a sheet steel container and a mild steel cone. It was designed to perforate a 5-ft. thick, reinforced concrete pillbox. Tests show that it will penetrate reinforced concrete to a depth of 55 inches with hole diameter tapering from approximately 5 inches to 1-3/4 inches. In concrete, the hole produced permits insertion of a Bangalore Torpedo for further demolition.

Like the M2A3 charge, the M3 may be found with two types of loading.

In using this charge, all personnel should be under cover and at least 100 yards away at time of detonation.

The above charges need not be clamped tightly against the surface to be punctured. If a hole is desired in a vertical wall, the charge can be propped against the wall with a forked stick or suspended from a wire like a picture frame.

The British also had two well-known demolition charges, the Beehive and the General Wade. (49, 55) The Beehive was similar to the U. S. charges described above. It was manufactured in two sizes, the M1 having a 6-1/2 lb. charge and a larger 50-lb. weapon having a 30-lb. explosive charge. (14) Both charges consisted of 25/75 (PETN/TNT). An 80° metal cone was used. The General Wade was a general purpose shaped charge having a 26-lb. filler of Pentolite. It was built around a metal semi-cylinder.

The British also had another demolition charge called the "Hayrick" or "Stook." (49, 55) This charge was produced primarily for bridge demolition. The Hayrick is a linear, wedge-shaped charge with cuts along a line.

The U. S. Navy Bureau of Ordnance developed the Demolition Charge Mark 22 Mod 0 for quick scuttling of explosive-filled, drone boats by cutting a 10-in. by 20-in. hole through the 1/8-in. bottom plate. The charge is shown in Fig. 44. A watertight standoff sleeve allows the charge to function under water. It may be used for cutting through mild steel plate up to 1/2-in. thick. The container is furnished empty, being loaded with 1-1/4 lbs. of plastic explosive prior to use.

A Cable and Chain Cutter Mark 1 Mod 1 was developed by the U. S.

Navy Bureau of Ordnance for use by underwater demolition teams, though its use is by no means limited to work of this type. The charge was designed to cut cable, chain, or similar material which might be employed as obstacles to landing craft. This horseshoe-shaped container employs an 80°, V-shaped, mild steel liner and is filled with 2 lbs. of plastic explosive prior to use. The cutter is provided with a spring-loaded clamping arm which locks it in place on the object being attacked.

The charge is capable of cutting 2-in. steel cable, 1-1/2-in. steel anchor chain, or other material which will fit between the horseshoe jaws. Needless to say, the cutter is destroyed during detonation, and if used out of water, personnel should be under cover to avoid flying fragments.

ORDNANCE DISPOSAL CHARGES

Several types of shaped charges have been developed by the U. S. Navy Bureau of Ordnance for the disposal of explosive-filled ordnance. These, in general, consist of either small, beehive-type charges for initiating "low-order" detonations, or of linear and curvilinear charges for sectioning explosive-filled ordnance.

Figs. 45 and 46 show the use of the Cavity Charge Mk2 Mod 0 for opening U. S. and German bombs by the initiation of low-order detonations. The shaped charge is shown to the right of the bomb in Fig. 45(a), and on top of the bomb in Fig. 46(a).

Cavity charges employed for such work use a small charge of plastic explosive (such as Composition C-3), the explosive being loaded just prior to use. Relatively large standoffs are used, and in attacks

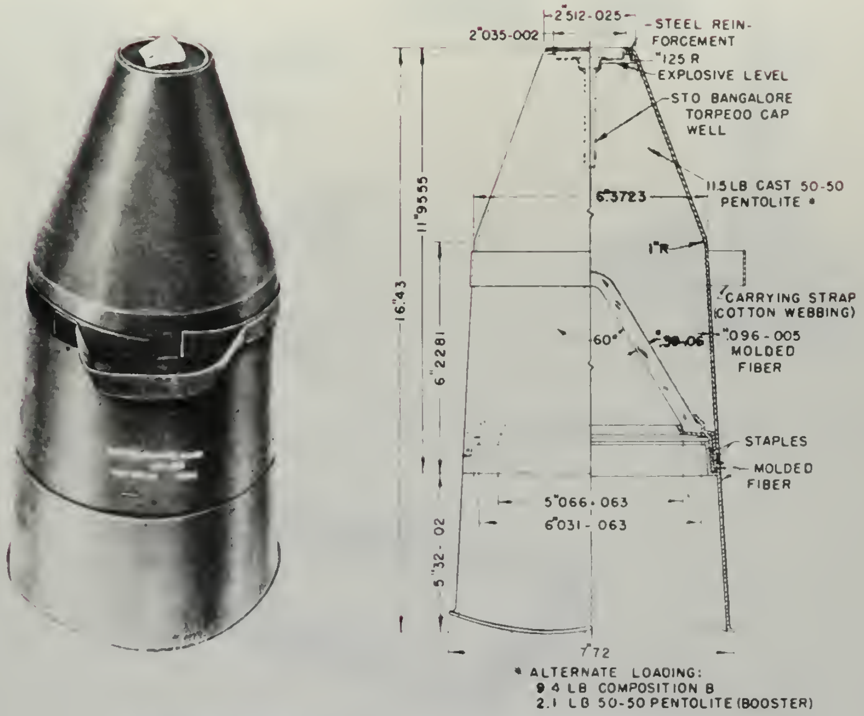


Fig. 41.—*Shaped Charge, 15-lb., M2A3.* (62)
(United States)

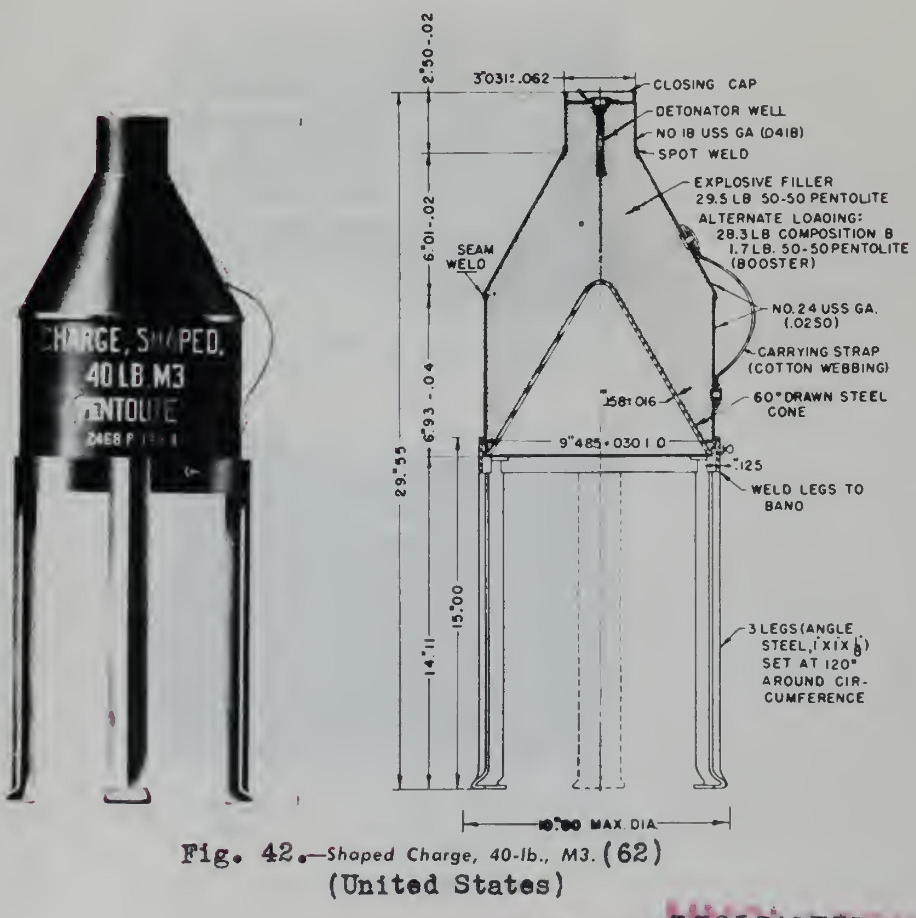
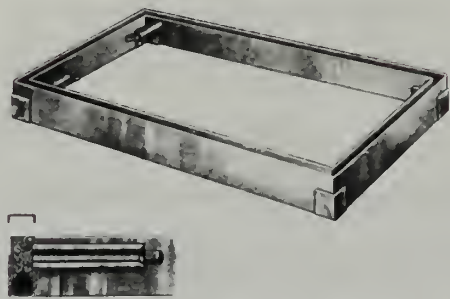


Fig. 42.—*Shaped Charge, 40-lb., M3.* (62)
(United States)

Fig. 43.—Two-inch Steel Cable and 1½-inch Steel Anchor Chain Cut by Demolition of Cutter. (62)
(United States)



Demolition Charge Mark 22 Mod 0.

Demolition Charge Mark 22 Mod 0 Placed on ⅛-inch Steel Plate Supported on Surface of Water.

Fig. 44. ⅛-inch Steel Plate Showing Rectangular Hole Cut by Demolition Charge Mark 22 Mod 0. (62)
(United States)

on bombs and projectiles, approximately 80% may be expected to result in low-order detonations. Cavity charges have also been applied to the disposal of buried ordnance.

Linear and curvilinear charges have been used successfully for the opening of thick and thin-cased explosive-filled ordnance. Under optimum conditions, linear cavity charges can be expected to penetrate to a depth equal to 80% of the width of the cavity lining in mild steel targets massive enough to withstand the attack, and to a depth equal to one charge width in mild steel targets where the depth of the target is no greater than the charge width.

The successful sectioning of thin-cased ordnance depends upon cutting completely through the ordnance case and to a sufficient depth into the explosive filling to obtain sufficient shearing action to separate the explosive.

Linear cavity charges with V-shaped linings of 120° apex angle have been preferred for sectioning thin-cased explosive-filled ordnance. This is due to ease in manufacture over charges with an 80° liner. Charges of the former type have been used for sectioning steel cases varying in thickness from 0.06 inches to 0.30 inches. Cavity charges with 80° liners have been used for sectioning cases thicker than 0.30 inches, where the necessarily larger charge increases the ease of manufacture and filling.

Fig. 49 shows a German G type mine before and after sectioning by a curvilinear cavity charge. Curvilinear charges for such purposes can be rolled from thick sheet brass.

Fig. 48 shows a German G.P. bomb before and after sectioning by a linked linear cavity charge. When linked linear charges are applied

to cutting on curved surfaces, gaps will necessarily appear between the explosive filling of individual links. Best results are obtained when these gaps are filled with plastic explosive. The links used are generally 3 or 6 inches in length and are joined together by means of wires soldered at the base of the links.

In order to assist mine and bomb-disposal personnel in the preparation and use of linear cavity charges, the Linear Cavity Charge Calculator, shown in Fig. 47, was developed from information derived in a fundamental investigation of linear cavity charges of plastic explosive conducted by the Ordnance Investigation Laboratory.

The face of the calculator contains five different scales for cavity linings of both 80° and 120° apex angles, as follows:

S = Standoff distance.
W (black) = Width of charge.
W (red) = Desired depth of cut into massive targets.
H = Height of plastic (Composition C-3) used in charge.
T = Thickness of mild steel required for cavity lining.

The back of the calculator includes instructions for its use, penetration equivalents for cavity charges in various target materials, a rule in inches, and a table of decimal equivalents.

The use of the calculator is illustrated by the following example: (62)

PROBLEM

It is desired to make a cut 0.8-inch deep in a mild steel plate 1-1/2-inches deep, using the minimum quantity of plastic explosive.

SOLUTION

Since linear cavity charges of plastic explosive fitted with cavity lining of 80° apex angle are efficient cutting charges and the target plate is massive enough to withstand the attack without spalling, the hairline is set to 0.8 on

the red W scale for the 80° angle. The required charge specifications are then read from the rule as follows:

Charge width.................. 1 in.(black W scale)
Height of explosive (H).................... 1.2 in.
Thickness of liner (T)................. 0.040 in.
Optimum standoff distance (S)............ 0.6 in.

A linear cavity charge made to these specifications may be expected to penetrate to a depth of 0.8 inch into the given target plate.

For additional information on opening explosive-filled ordnance, OP 1720 should be consulted.

MISCELLANEOUS

CABLE CUTTER

A specialized item to be used as an emergency cutter for the towing cable in a glider pick-up system has been developed by the Army Ordnance Department. (62) It is called the Cable Cutter M1 and is somewhat similar to a cable cutting device patented by C. O. Davis (11) in 1943. In practice, the cutter is placed below the airplane in a shielding box through which the tow cable passes. The shaped charge container is made of fiberboard to reduce missile hazard. The box stops all fragments which might damage the plane. With a 0.06 lb. charge of Pentolite, the cutter will easily sever a 3/8" steel tow cable.

MINE CLEARING SNAKE

A "twin tube mine clearing snake" for clearing a passageway for men and vehicles through a mined area has been patented by Greulich. (16) This snake consists of a number of metal sections which may be bolted together in the field and pushed into a mined area. These sections have a tube along each outer edge containing an explosive material in

(a) Cavity Charge Mk 2 Mod 0 directed for attack.

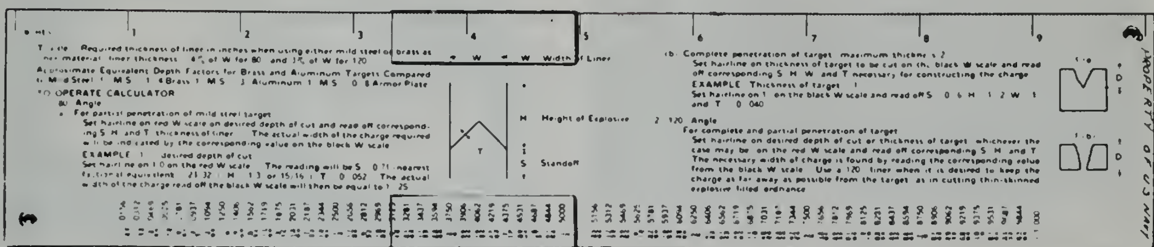
(b) Bomb opened by low order detonation of explosive filling initiated by attack of Cavity Charge Mk 2 Mod 0. The section torn from the case was blown approximately 200 yards.

Fig. 45.—*U.S. 500-pound G.P. Bomb AN-M63.*(62)

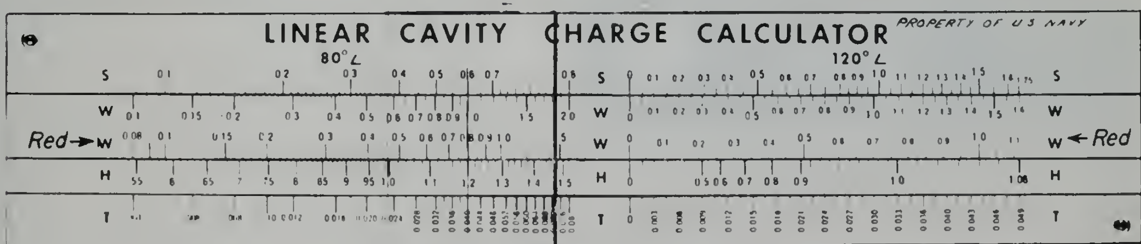
(a) Cavity Charge Mk 2 Mod 0 directed for attack of 250-kg. German G.P. Bomb.

(b) 250-kg. German G.P. bomb opened by low order detonation initiated by attack of Cavity Charge Mk 2 Mod 0. The bomb case is ripped open and the explosive filling is broken up and scattered.

Fig. 46. —*250-kg. German G.P. Bomb.*(62)



(a) Rear View



(b) Face View

Fig. 47. Linear Cavity Charge Calculator. Hairline is set for computing specifications for charge required for cutting 0.8 inch into a 1-1/2-inch thick target of mild steel. (62)

(a) The charges are linked together by means of cotter pin joints incorporated in the standoff legs placed for sectioning of the bomb.

(b) Sectioned by the detonation of the linked linear cavity charges.

Fig. 48.—250-kg. German G.P. Bomb. (62)

(a) Cavity charge placed for sectioning.

(b) Cavity charge as seen from unit compartment or tail end of the mine. Note the standoff provided by wire legs.

(c) Blasting cap placed in booster of approximately 10 gr. of Composition C-3. The blasting cap does not extend into the charge proper.

(d) The section cut from the mine case has been thrown approximately 10 feet.

Fig. 49.—German G Ground-Sea Mine. (62)

the form of a V-shaped wedge facing outward. It is contended that on detonation, the shaped charges produce a maximum sidewise destructive effect and clear a maximum possible width of path through a mine field. This is a dubious issue, however.

FUZES

The use of the shaped charge principle in nose impact fuzes of shaped charge projectiles was illustrated in this chapter in the section on projectiles. The use of percussion type nose fuzes incorporating a small shaped charge which upon impact initiates a booster at the rear of the charge is becoming more widespread, as its action is faster than the functioning of a base fuze. Rapid initiation is extremely important in the case of high speed, shaped charge projectiles.

SUMMARY

1. The shaped charge principle has been incorporated into almost all types of military weapons. The major powers made widespread use of it during World War II.

2. Weapons incorporating the shaped charge have found application principally in the destruction of pillboxes, bridge demolition, and in anti-tank warfare.

3. A variety of charges of both the beehive and linear types have been designed and proven effective for the disposal of explosive-filled ordnance.

4. A calculator has been prepared to assist mine and bomb disposal personnel in the preparation and use of linear cavity charges of 80° and 120° wedge angles.

5. The penetrating power of shaped charge weapons is practically independent of the striking velocity. Statically-fired charges are in general more effective than high speed charges.

6. Shaped charge weapons give the foot soldier the striking power of light and heavy artillery. With a 40-lb. charge he can blast a hole through 5 feet of reinforced concrete.

7. In the design of shaped charge weapons, maximum penetrating efficiency must frequently be compromised by other considerations such as ballistic requirements.

8. High rotational speeds of projectiles cause reductions in penetration to as low as 50% of static values.

9. The angle of impact of shaped charges is not as critical as it is with armor-piercing shells, making them more effective in high-obliquity attack of armored targets.

10. Conical liners are preferred in most applications where deep penetrations are desired.

11. The shaped charge principle has also found application in cutting cable and chain, in projectile fuzes, and in the rapid severing of glider tow lines.

CHAPTER VI

INDUSTRIAL APPLICATIONS

The publicity given to the military uses of shaped charges has naturally led to wide interest in its industrial possibilities. These have been investigated by several explosives manufacturing companies both foreign and domestic, the U. S. Bureau of Mines, several users of explosives, and others.

Use of the shaped charge is rapidly gaining in popularity, and as knowledge of the phenomenon and its mechanics becomes more wide-spread, it is believed that additional uses will be envisaged.

The following discussion deals not only with industrial applications which have proven successful, but also with others which appear to have practical utility. Many of these have been evaluated. Some have proven practical, others impractical, while a number of others although having practical utility, appear to be justifiable only in limited situations largely because of economy, noise, and blast considerations.

Since the number of applications thus far investigated is rather limited, most of them will be presented herein in order to inform the reader as to what has been done in this field, and what results have been obtained.

BREAKING BOULDERS

Of all the industrial applications of shaped charges, perhaps none has had as many contradictory views and opinions expressed about it as has had the use of shaped charges for breaking boulders. It is

therefore doubly interesting to study this problem and to view the controversial literature pertaining to it.

There is a definite requirement in quarries and in some mines for a means of breaking large boulders produced by primary blasting. The reduction of boulders to crusher size is termed secondary blasting. Some large quarries have as many as hundreds of boulders that must be broken by secondary blasting each day and the task is an important and expensive one.

One of two common methods of breaking large boulders is blockholing, or as the British call it "pop shooting," in which a shot hole is drilled and charged with a relatively small quantity of explosive. In this method the explosive energy is released within the boulder, even though the hole may be only a few inches deep.

The other method is termed plastering or mud-capping in which the explosive charge is laid on the surface of the boulder, after which the charge is covered with mud before firing.

Neither of the above methods incorporates the shaped charge principle.

During the period October 1945 - May 1946, considerable work was done at the University of Utah by R. S. Lewis and G. B. Clark to determine, among other things, the rock-breaking qualities of shaped charges. Types of charges experimented with were cylindrical charges having conical cast iron liners, hemispherical, and linear cast iron lined charges. These were employed in attacking solid granodiorite.

In 1946 Lewis and Clark stated that:

> "The relationship between penetrating power and rock-breaking power of Munroe jets has not been definitely established, but it is believed that the relationship is approximately linear. That is to say, the breaking power of a shaped charge increases in approximately direct proportion to the depth of penetration. Charges which are not correctly designed for achieving maximum penetration will not utilize the full possible energy of the explosive. Thus, for secondary breaking, as well as for penetration effect, liners must be annealed, optimum stand-off used and high powered explosives employed, properly packed in the charge, as well as incorporating other features of design. . . ." (25)

The conclusions reached as a result of the above breakage tests were:

(1) Linear charges exhibit a marked tendency to break rock of relatively small thickness along the line of the charge.

(2) Hemispherical charges proved effective in breaking rock, their breaking power being a function of the two shortest dimensions of the rock at the point of application. For effective results, the charge should be placed perpendicular to the two longest of the rock's dimensions. Charges placed on ridges tend to spend their energy on the ridge and fail to penetrate or break the rock effectively.

(3) Shaped charges have a definite and useful application in mining operations, both in secondary rock breakage, and drilling holes for blasting solid faces of rock. When fully developed and properly applied, the use of this type of charge will expedite blasting operations by saving time and labor with a proportional reduction in cost.

Additional experimentation was conducted by Clark, in cooperation with the Mining Department of the University of Utah, during the summer of 1946. Breakage tests were carried out on three sets of graded sizes

of concrete blocks employing 2" hemispherical shaped charges with aluminum alloy liners and aluminum cases. Fifty-four charges were used, each third of them being loaded with either 100% blasting gelatin, 60% N. G. dynamite, or 45% Gelamite.

The results of these tests indicated that for a given shaped charge, higher strength explosives are more effective in secondary breakage, the breaking power of the jet being assisted considerably by the impact blow of the shock wave of the explosion.

A few charges were also tried on boulders of iron ore and results indicated that larger charges are necessary to break boulder iron ore than non-ferrous rock or concrete.

In England, during World War II, a shaped charge called the General Wade was developed for the demolition of reinforced concrete emplacements and walls. It contained some 25 lbs. of explosives and was built around a semi-cylinder. Research work was subsequently carried out in England with small editions of the General Wade for breaking boulders, but results obtained were no better than those using a good plaster charge with some of the commercial explosives. In January 1947, R. Westwater of the Explosives Division of Imperial Chemical Industries Limited stated that "Present indications suggest that the breaking of boulders or secondary blasting in quarries would be performed more economically by the plaster shooting method, rather than by shaped charges." (55)

Boulder blasting experiments conducted by R. F. Preckel are outlined by R. W. Lawrence in The Explosives Engineer of Nov.-Dec. 1947. (24) Shaped charges of blasting gelatin (2" and 4" in diameter) were detonated against limestone boulders in comparison with similar charges

which were not shaped.

The results are summarized as follows:

(1) Solid charges produced better breakage than shaped charges.

(2) The penetrating ability of shaped charges is of little utility in breaking boulders.

(3) The boulder breaking ability of shaped charges is greater with no standoff than with standoff.

It is interesting to note the disparity of opinion of the above investigators.

On August 26 and September 17, 1949, a new method of secondary blasting for the reduction of boulders to crusher size was demonstrated by its inventor Laud S. Byers at Logan granite quarry in Watsonville, California. (46)

This method consisted of placing a shaped charge of modified design upon boulders, without mud-capping or artificial covering of any kind. This new charge was called the "multiple-jet shaped blasting charge" and is covered by U. S. patent 2,513,233 of June 27, 1950.

It should be mentioned that in determining a suitable design for his blasting charge, Byers used a trial and error method, testing literally hundreds of charges on steel plates. If the results looked encouraging, he next tried them out on actual boulders. Numerous trips had to be made to the proving grounds before arriving at a satisfactory design which is shown in Fig. 50. This charge was composed of two concentric cones of approximately 30 and 60°.

The nature of the disruptive ripping effect obtained with this charge as contrasted with the relatively clean, penetrating effect of

conventional conical charge is shown in Fig. 51.

In the initial tests at Logan Quarry, the majority of the granite boulders, estimated to weigh from 1-1/2 tons to approximately 20 tons each, were broken to 100% crusher size at the first blow, with a noticeable absence of fines. The crusher size tonnage produced ranged as high as 2.05 tons of rock per pound of explosive used. 1-1/2, 2, and 6-lb. charges were employed, the former having a molded, paper-pulp container which was completely disintegrated by the explosion, and the latter two having aluminum containers which are readily oxidized by the heat of explosion, thereby eliminating the danger of flying missiles.

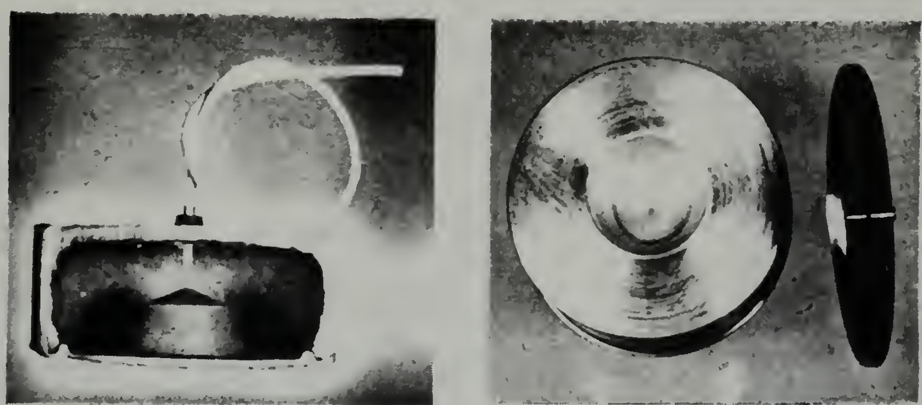


Fig. 50. The "multiple-jet shaped blasting charge." (5)

The principle of this new charge, which is now known as the "Plurajet" is illustrated in Fig. 52 and is described by Eyers (6) as follows:

> "These actions take place upon detonation. First, the wave front shown travels downward from the concentrated end of the blasting cap and collapses the top apex of the cavity thereby creating the primary jet (P), which starts boring a hole into the boulder.
>
> "The second action is collapsing of the side apexes, creating secondary jets (S-S_1) which meet and interfere with the primary jet at the point of convergence, as shown. The action of these excited gases at this point of convergence

is that of an 'implosion,' the effect of which serves to rip the boulder apart.

"The third action, immediately following, is that of the shock waves, shown in the illustration, which have been deflected towards the boulder and serve the purpose of completing the shattering process. The blow is of such high intensity and of such short duration that the shattered pieces are dropped in toto before they have had a chance to pick up momentum and fly through the air."

This theory of Byers is certainly a novel one and is not in accord with our present concepts of wave propagation. Byers depicts the propagation of the detonation wave much as the flux lines in a magnetic field of force rather than in terms of a spherical wave front.

The reason for the spreading of the jet at the "point of convergence" is also not clear. It would appear that the effect of the dual cone should not be much different from that of a single cone.

Fig. 51. Two views of a steel plate after attack by the "multiple-jet shaped blasting charge." (5)

Figure 53 shows a newer type of "Split-jet" shaped blasting charge known as the "Plurajet." According to Byers, this unit produces a blow four to five times that of the same explosive even when confined by mud-capping. The annular ring surrounding the central cavity is based on the same "split-jet" principle, and was found to have greater striking force than a circle of individual cavities surrounding the central one.

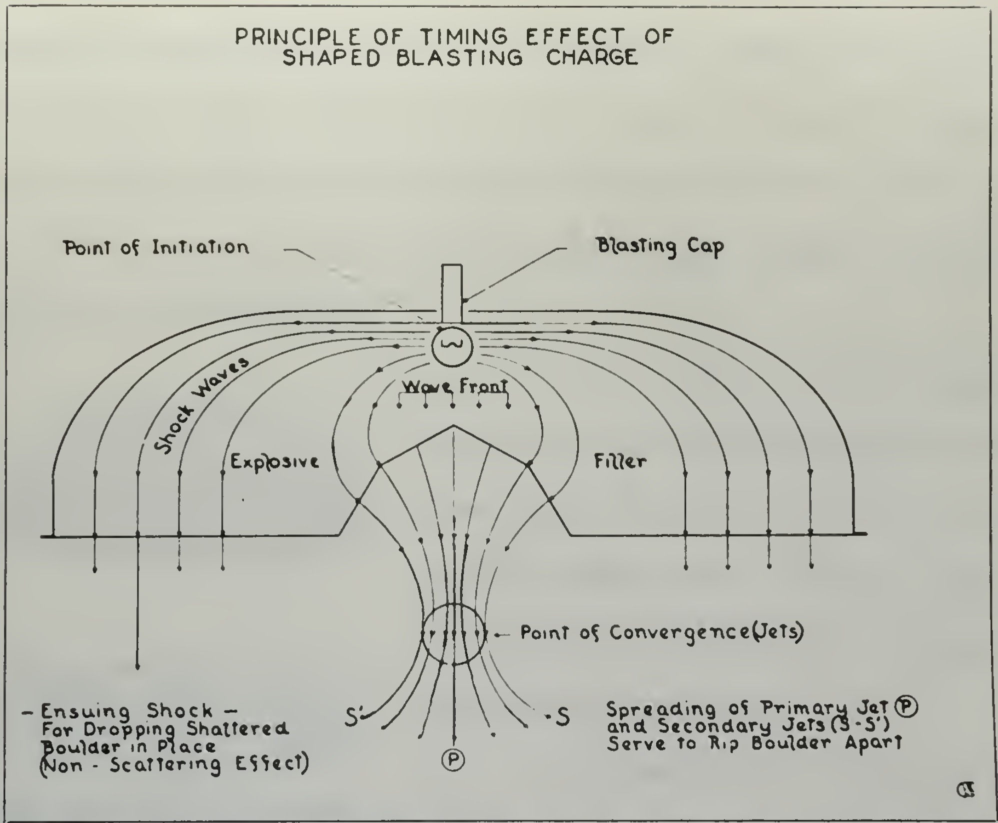


Fig. 52. Diagram illustrating the Byers' principle of the "multiple-jet shaped blasting charge." (5)

A graphic example of the effectiveness of this new Plurajet charge can be seen in Fig. 54.

In this instance, a medium size charge was placed on the side of a dense granite boulder, weighing approximately 18 tons. The indentation where the charge was hung can be clearly seen in the photograph. Byers states this boulder was lying within 40 feet of a new electric shovel worth $125,000, which was not moved prior to the blast. The farthest fragment thrown was not more than 15 feet from the explosion.

The advantages claimed for the Plurajet blasting charge are legion.

One of the distinct advantages claimed is the man hours saved over block-holing and mud-capping. In a recent demonstration in Strasburg, Va.,

16 boulders weighing from 1/2 to 12 tons each (a total of 80 tons) were broken to crusher size by the work of only one man in 30 minutes. It was estimated by the quarry operator that it would have taken at least 5 times the man hours using the block-holing method. This meant a great gain for production.

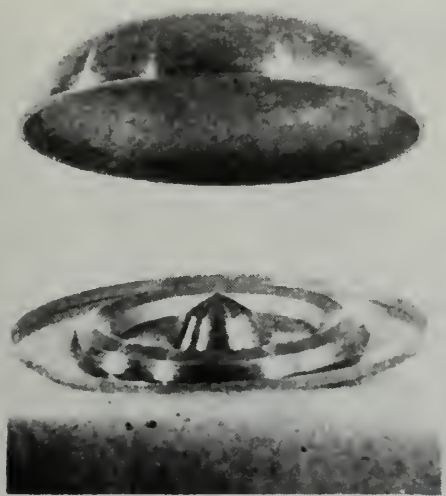


Fig. 53. The Plurajet shaped blasting charge shown with cover removed. (6)

Also, as there were no broken pieces of rock thrown through the air, the shovel was left only 60 feet away on the quarry floor, thereby saving time of the shovel operator and wear and tear on equipment.

As there was no scattering of sharp pieces of rock, it was unnecessary for the bull-dozer to clear the quarry floor for the waiting rubber-tired rock trucks.

The safety factor to both men and equipment, by reason of absence of flying fragments, is also pointed out as an important advantage.

Whereas in block-holing, the actual cost of explosive is small; the cost of labor to drill and load holes is considerable. Then there is also the accompanying disadvantage of throwing fragments in all directions.

Plastering, or mud-capping, uses many times the amount of explosive as block-holing and requires mud of the proper consistency. In many quarries and mines, mud or even wet sand is not always readily available, and its preparation constitutes a considerable item of bother and expense.

The multiple or split-jet blasting charge has the advantages of both the block-holing and mud-capping techniques. It eliminates the need of drilling holes in boulders, and accomplishes the results of mud-capping without mud or any other covering. It eliminates many somewhat intangible expenses which are properly chargeable against

Fig. 54. 18-ton granite boulder after attack by a "Plurajet" charge. (6)

such costs as, for example, cost of jack-hammers, drill-bits and steel, wages of jack-hammer men, amortization of cost of jack-hammers, hose, etc., cost of moving power shovels, compressors, and other equipment to be safe from flying fragments, costs of bull-dozers to gather together scattered pieces, and to clear quarry floors for rubber-tired dump trucks, the time and wear and tear on costly shovels having to fight boulders and keep moving them out of the way until drilling and blasting crews can come in and shoot them, while the idle trucks stand by waiting for their loads.

The noise of the Plurajet is somewhat greater than that of blockholing, but is less than that of mud-capping.

In a concussion test recently made, where 32 Plurajet charges were fired simultaneously, none of the glass window panes which were set up at 100, 150, and 200 feet surrounding the group of boulders being blasted, were broken or cracked. The explosive filler is also in a high classification as to absence of toxic fumes.

Plant facilities (5) are being completed near Martinsburg, W. Va. to produce the Byers' shaped charges in commercial quantities. Loading and sealing of the blasting units will be done by a specially-designed machine with a capacity of from 250 to 400 completed units per hour. The magazine storage capacity is from 50,000 to 100,000 completed units.

As seen from the above, while some shout the praises of the shaped charge for breaking boulders, others deem it no better than similar solid charges. While some feel that maximum breakage is obtained when the maximum penetrating properties of the shaped charges are utilized, such as optimum standoff, etc., others maintain that the penetrating ability of shaped charges is of little utility in breaking boulders, and that breakage is greater with no standoff than with standoff.

No doubt the Byers' charge is an effective rock breaker. However, comparative figures have not been given showing the breakage attainable with a charge of similar external dimensions and utilizing the same explosive, following the lines of the tests conducted by Preckel. It is the opinion of some experts that an unshaped charge of the same detonation rate explosive and similar external dimensions would be just as effective, if not more so, than a shaped charge, and considerably cheaper. What is desired is a relatively flat, single-package charge. It is believed that

such a charge is more effective than an equivalent amount of dynamite sticks due to the higher charge density and the better contact with the boulder under attack. These are both due of course to geometrical considerations alone.

OIL WELL CASING PERFORATING

When a well is drilled, it is lined with a casing to prevent cave-ins or influx of water from adjacent formations. This casing consists of at least one steel tube, and sometimes two or three concentrically arranged and jacketed with cement.

After a well has been producing for some time, it is not uncommon for it to "run dry" or for its production to fall off due to any of several causes which will not be discussed here.

The idea of opening producing formations by firing steel bullets through casing and cement was conceived, and on December 12, 1932 the first gun perforating job was accomplished on an oil well which had been off production for three years and was ready for abandonment. This work was done by the Lane-Wells Co., and 15-1/2 years later in June 1948, this company celebrated its 100,000th gun perforating job by reperforating this same well which was still producing.

Until 1947, casing perforating was done exclusively by the gun perforator method, which consists of lowering into the well to the desired level a steel cylinder housing an ingeniously arranged battery of short-barreled pistols. Each weapon is loaded to shoot a bullet through the casing, thus opening channels in the sand through which the oil and gas can flow. The propellant used in the guns has a cellulose nitrate base and is ignited electrically.

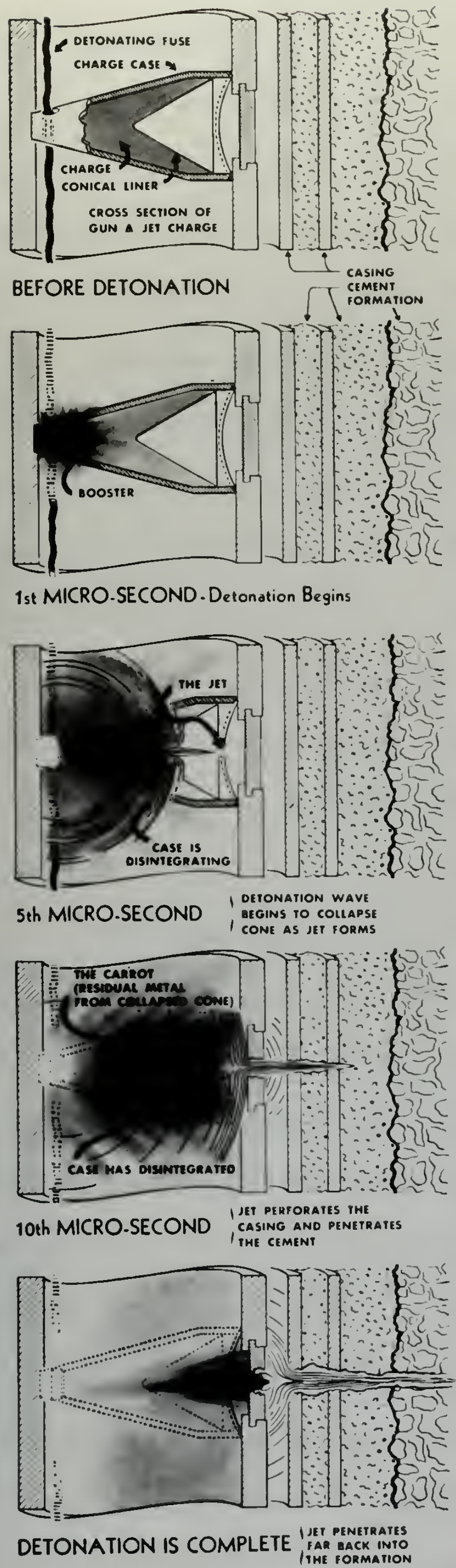


Fig. 55. Time sequence in the perforation of an oil well casing by a jet perforator. (3)

This seemed for a long time to be the only means of making holes where they were needed. In view of the thicknesses of the well casings, however, it was frequently questionable as to whether or not all the bullets passed through the walls into the oil strata.

In 1946 casing perforating tests employing small shaped charges in plastic containers were conducted on the surface under simulated conditions with extremely promising results. (31) The development of the "Jet Perforator," as the shaped charge is generally referred to in the petroleum industry today, engaged the attention of several explosives concerns. The modern jet perforator is made with a plastic case into which the explosive is pressed. A conical liner of copper is used as it disintegrates almost completely with very little slug metal, leaving the perforations clean and open.

Several sizes of charges are currently in production, two typical sizes being a 28-gm charge which makes a hole approximately 1/2" in diameter in the casing, and a 21-gm. charge which makes a

3/8" diameter hole.

As of July 1950, the jet perforator method had gained such popularity and fame that it had absorbed about one-third of the perforating business in the oil fields. The DuPont jet perforator is claimed to have up to 300% more penetration power than gun perforators.

The time sequence in the perforation of an oil well casing by a jet perforator is shown in Fig. 55. In practice, the jet perforators are fitted into a carrier, which consists essentially of an alloy steel tube with ports drilled through the wall in a spiral formation (generally 120° phasing on 3" centers). See Fig. 56.

Carriers for jet perforators have been made to hold approximately 12, 24, or 40 charges which in general have 3-in. or 6-in. spacing. In a number of cases, requests are made for densities of 6, 8 or 12 shots per foot.

The perforators, after having a primacord detonating fuse threaded through a ferrule on the initiating ends of each charge, are inserted in the carrier, as shown in Fig. 57, and securely fixed in position in alignment with their respective ports. The ports are externally sealed with pressure-tight closures to exclude the well fluids (oil, mud or water) which if allowed to enter the cones of the shaped charge, would nullify the Munroe effect. The lower end of the carrier is sealed off or another gun is connected, if more than one is needed. The free end of the primacord is brought up through the top of the carrier to the detonating sub, where it is connected to an electric blasting cap which in turn is connected by means of conductor cable to the surface operating truck. Enough air space is left inside each carrier to cushion the blast and allow the explosion gases to bleed out over a relatively long period

of time. Otherwise, the resultant blast would probably crack the well casing.

Lowering is done by remote control from the perforating truck. An electric cable is run from the truck to a pulley positioned over the

Fig. 56. Lowering a casing perforating charge carrier. (18)

well, and the carrier is attached. Built into the pulley are mechanisms for measuring accurately the weight load on the cable and the exact length unreeled. These measurements are transmitted electrically to a panel board in the truck. See Fig. 57. As the charge is lowered, the operator watches the weight indicator to make sure that the carrier has not been stopped by an obstruction in the well. When the carrier is "on zone" at the desired depth, the operator initiates the detonation.

The dial indicator shows the carrier is now "on zone" at 7,899 feet—and the operator fires the shot.

Close up of the gun-loading operation. The shaped charges must be carefully aligned with gun ports.

Fig. 57. Jet perforating operations. (3)

Since all perforators are linked by a single piece of primacord whose velocity of detonation is approximately 22,000 feet per second, the detonation of all charges is practically simultaneous, after which the empty carrier is pulled out of the well.

The number of holes made may vary from about a dozen to several thousand, depending upon the depth of the producing zone and how many perforations are required per foot. In any case, the job is done quickly and effectively.

Jet perforating can be done at higher temperatures than bullet perforating, an important factor when one considers that some deep wells are 350°F. or hotter. R. Harcus has presented a summary of casing perforating operations on a commercial basis over a period of approximately six months. (18) The temperatures recorded at the shooting depths were almost consistently over 100°F. with many in the vicinity of 150° and one of 245° in an 11,000 foot well. Since the operation of lowering and firing a carrier ordinarily takes a relatively short period of time, it might be assumed that the jet perforator explosive charge would not have sufficient time to be affected to any great extent by the well temperatures. However, all eventualities must be taken into consideration in this respect. For example, should it be necessary to perforate a very deep well where temperatures range in the 300's, and should it be discovered after a long journey down that the carrier has encountered an obstruction some thousand feet short of its mark, to withdraw the carrier would present a grave danger to operating personnel from the possibility of what is known as a "cook off." To haul the carrier up to a cooler level and allow it to sit for a reasonably safe period of time before withdrawal might result in a "cook off" in an undesired region of

the well, with possible penetration of the casing, although the jet effect and resultant penetration would undoubtedly be greatly reduced since the charges would not be initiated at the proper position.

Hence a considerable burden is placed on explosives to be used for oil well work. Pentolite, for example, which otherwise has all the qualities necessary for efficient shaped charge operation, is unsatisfactory as it has the low melting point of about 180°F.

An excellent explosive has been developed for jet perforator work. When loaded at high density, it is relatively insensitive to shock; has a high rate of detonation and a high energy content; will burn without detonating, and is sensitive to primacord only when the primacord is threaded through the end of the charge designed for its entry. In addition to these features, it is designed to withstand a temperature of 325°F. for 24 hours and a temperature of 350°F. for 1 hour. If excessive temperatures are encountered, it will fume off into a gas -- excluding all possibility of premature or unwanted detonation due to high temperature. These qualities, together with the insulating property of the hollow tubular carrier, make the explosive entirely feasible for use at any well temperature encountered to date. This explosive is a waxed RDX composition. A small portion of unwaxed RDX, adjacent to the ferrule, acts as a booster charge for the main charge.

A double-ended charge has been designed and proven successful. It is detonated at its midpoint and emits a jet from both ends. In addition to doubling the number of holes in the casing with any given number of charges, this design enables a greater percentage of the energy to be utilized in penetrating the casing, with correspondingly less ex-

traneous energy available for further detrimental effect on the pipe.

While the adaptation of the lined shaped charge principle to petroleum production is by no means complete, it has advanced to the stage where its use is an established fact and it appears to be without a doubt the most effective known means of perforating well casings.

In spite of the greater effectiveness of jet perforators, gun perforator methods continue to be used in the majority of cases due to their cheaper cost. Jet perforators are used principally for the more difficult shots.

The oilman today is frequently faced with the need for making the decision as to whether he should employ the cheaper gun perforator method with the possibility of failure of penetration and subsequent recourse to the jet method anyhow, or whether he should use the more expensive jet perforators in the first place. Needless to say, jet perforators are steadily gaining in popularity.

A new technique of oil well shooting has been developed by James Murphy (41) which also utilizes the shaped charge principle. This method involves the use of specially-designed star, wedge, and conically shaped charges for the selective shooting of certain strata. Experimental work was being conducted in 1947 under "Patent Applied For" provisions; however, nothing is known of the present status of this work.

TAPPING OPEN HEARTH FURNACES

One of the latest industrial developments of the shaped charge is its use in tapping open hearth furnaces. Although not as yet in full-scale production, "jet tappers" as they are called, are currently being used as a routine procedure in three shops of one of our major steel

companies, with a monthly consumption of approximately 500 charges. One of these shops has been using them since August 1950, hence it is obvious that they are out of the experimental stage.

The conventional method of tapping open hearth furnaces is by means of the oxygen lance. This method involves the lance operator's standing by the runner and inserting his lance into the furnace tap

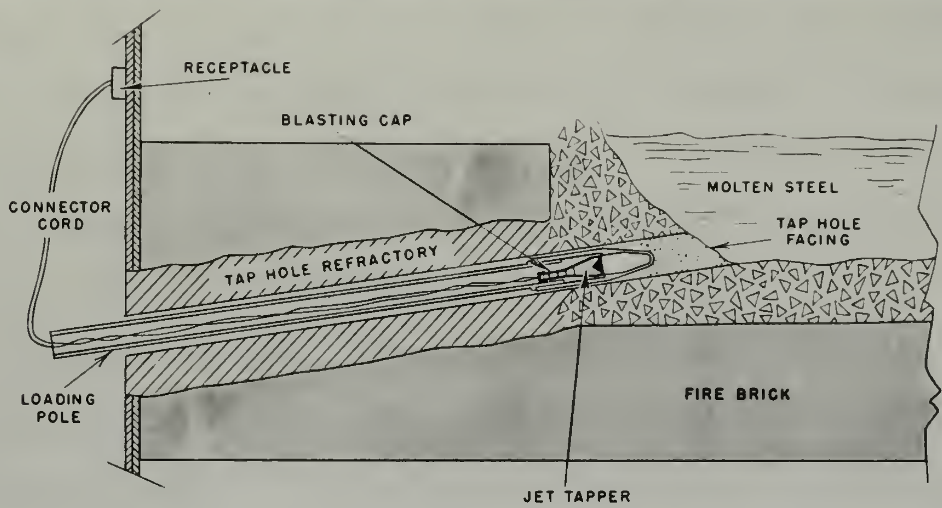


Fig. 58. Cross section of open hearth furnace tap hole showing Jet Tapper in position for firing (13)

hole. As the lance burns through the tap hole facing and the molten steel starts to flow down the runner, he must quickly withdraw his lance and move clear of the runner to keep from being burned.

In the jet tapping method as developed by the DuPont Company of Wilmington, Delaware, the charge is shoved into the furnace tap hole on the end of an 8-foot spiral-wound paper tube after which the operator retires to a remote station and fires the charge electrically. All units of the assembly are expendable.

Fig. 58 shows a cross-section of an open hearth tap hole with jet tapper in firing position. The tapper consists of a 2-ounce explosive

charge of RDX enclosed in a plastic case which is surrounded by a hollow bullet-shaped insulating body with walls 1/2-inch thick. The RDX is relatively insensitive to impact and friction, and if heated to a sufficiently high temperature, will burn without detonation. In one test, a case of 24 Jet Tappers was completely soaked in a bonfire of kerosene-soaked wood without any sign of a violent reaction. In another test, six tappers were laid side by side between steel plates and a 150-pound weight was dropped 9 feet onto the upper plate. Although the charges were completely crushed, no detonation resulted. The tappers are detonated by a special high temperature electric blasting cap situated in a well in the back of the plastic case.

Although the caps will eventually detonate spontaneously after prolonged exposure to temperatures above 500°F., experience has shown that they will stay in a hot tap hole for 3-8 minutes without detonating when used in the jet tapper assembly. This allows more than enough time for normal firing methods to be carried out.

DuPont jet tappers will penetrate more than 6 inches of cold steel. They will penetrate somewhat deeper into hot steel, although target temperature has less effect on the depth of penetration than on the diameter of the hole produced. A jet which punches a hole about 3/8 inches in diameter at atmospheric temperature will make about a 1-inch hole at 1500°F.

Jet tappers are not recommended for use whenever there is any indication that a heat is likely to break out of its own accord, even though tests have indicated that the cap will not detonate for at least a minute even if the assembly is floating in molten steel.

The advantages claimed for the jet tapper over oxygen lancing from both operational and safety standpoints are as follows:

1. It is unnecessary for anyone to stand by the runner when metal starts to flow.
2. The danger of burns from faulty connections in oxygen lances is eliminated.
3. Heats can be tapped at exactly the desired time, avoiding off-specification heats resulting from delayed taps. This is especially important in the case of manganese steels.
4. Taps start out at full flow rate, thus reducing over-all tapping time and ladle skull.
5. The uni-directional action of Jet Tappers reduces tap hole maintenance and assures perfect alignment of the tap hole.
6. The need for bars to knock down ridges in front of the hole is practically eliminated.

The shaped charge method of tapping is now available for general use and it is believed that it will soon win over many followers.

DRILLING HOLES FOR BLASTING

The outstanding characteristic of the shaped charge is its large penetration ability; hence a considerable amount of investigation has gone into the evaluation of the shaped charge as a means for drilling holes for blasting in lieu of using drilling machinery.

In 1948 the U. S. Bureau of Mines completed extensive tests to determine the effectiveness and limitations involved in the use of shaped charges for drilling blast holes in underground mining. (12)

All of the shaped charges used were U. S. Corps of Engineers military demolition-type in two sizes, the 15-pound M2A3 and the 40-pound M3 charge. Nearly 140 charges were fired in various types of tests. These involved testing the effects of using various standoffs ranging from 0 to 360 inches and also superimposing the firing of as many as 17 charges on a single borehole. Boreholes produced in greenstone and epidosite ranged as high as 111 inches in depth and 12 inches in diameter. Peak-pressure diaphragm meters were placed at various stations along the passageways.

The results of these tests showed that the shaped charge has no practical application in drilling blast holes in underground mines. At an estimated cost of $8 per foot of hole, plus considerable spall produced by the most efficient single shots with the M3 charge, the cost was over 20 times that of producing a better hole with a rock drill.

The concussion effects would prohibit its use in many mines, and the excess carbon monoxide gas liberated by the 50/50 Pentolite explosive would be an additional hazard when used underground.

Peak-pressure meter readings indicated that in a straight mine passageway, the blast effect of the M3 charge would be harmful to personnel at distances up to approximately 1,200 feet.

The practicability of blasting drill holes in the ground for seismic prospecting has also been investigated. (24) For this purpose, 3-1/2-inch diameter charges of blasting gelatin weighing about 2-1/2 pounds, and 8-in. diameter charges, weighing about 10 pounds were used. Conical copper liners of 53, 70, and 90° were employed. The 2-1/2-pound charges produced holes up to 3-1/2 feet deep and 3 to 6 inches in diameter, while the 10-pound charges produced holes up to 7 feet deep

and 8 to 15 inches in diameter. In all cases, the bottom half of the hole was filled with loose dirt which could be cleaned out easily. With three successive 2-1/2-pound charges, depths up to 6 feet were produced, and with three successive 10-pound charges, 8-9 ft. depths were obtained. From the above, it appears that the shaped charge would be useful in seismic prospecting in remote places which are ordinarily inaccessible to standard drilling equipment.

The use of the shaped charge as a quick means of drilling shot-holes for blasting has been investigated in England. R. Westwater of the Explosives Division of Imperial Chemical Industries, Limited, found that it was possible to produce a good shot-hole in sandstone approximately 4 feet deep using a 3-3/4-pound conical charge. (55) He concluded that while quite satisfactory, the use of shaped charges for this work is still fairly expensive and can only be considered as a means of obtaining a shot-hole in very special circumstances. Such circumstances do occasionally arise, however; e.g., in a case where the time of drilling is limited, or where only a few shot-holes are required in an inaccessible position, or where power drilling is not available.

As pointed out in Chapter V in the section on demolition charges, if blast holes are to be loaded immediately with a secondary explosive, a non-metallic liner should be used in order to eliminate the presence of a hot slug. Glass liners are satisfactory for this purpose.

BLASTING IN UNDERGROUND MINES

As stated in the previous section, investigations by the U. S. Bureau of Mines have indicated that the use of military-type demolition charges for drilling blast holes in underground mines is impractical.

However, work conducted by J. T. Warren at the National Tunnel & Mines Company property near Tooele, Utah (53) indicates that the shaped charge does have some practical applications in underground mining.

Warren experimented with two sizes of shaped charges of rather crude construction. The smaller charge, holding 1-1/4 sticks of powder, was used for the reduction of boulders on grizzlies and in scrams, while the larger charge of nine sticks was used mainly for breaking up finger hang-ups. With the small size, it was possible to place at least 10 charges in the time that it takes to drill, load and shoot one charge by the conventional block-hole method. With the larger size, Warren states that:

> "One charge has many times done the work of three boxes of powder and in a few moments as against several days. . . . Experiments were so successful that the charges were immediately put into practical use and as far as we were able to put the "bomb" into use (production of the cans was slow) we increased our tons per man shift over 30 per cent and consequently effected a material cost saving. We figure that with these bombs we break four tons per pound of powder, or that the powder cost per ton broken is less than 4 cents."

In contrast, powder consumption for maximum-size boulders broken by the ordinary blasting methods employed at the National Tunnel & Mines property has been estimated to average about 1 lb. of explosive per 1 to 1-1/2 tons of rock broken. Warren claims that use of the shaped charge has resulted in lower powder consumption, shorter smoke delays, a lighter burden on the ventilation system, and increased production.

According to Huttl (20), the shaped charges used at the National Tunnel & Mines property had a hemispherical steel liner made slightly less than a full hemisphere, and an outer cylindro-conical sheet-iron case. Wire eyelets were soldered to the outer shell to permit tying it

to a blasting stick which was then used to hold the shaped charges against large overhead boulders trapped in finger raises. Since high-speed, military-type explosives produce toxic explosion products, a 45% strength dynamite was used. Best results were obtained with zero standoff.

The above writers may be overly optimistic about the results obtained in breaking rock in mines with shaped charges. No mention is made as to whether any tests were conducted with charges of approximately the same outside dimensions as the shaped charges used, but with the cavities filled with explosive. Several authorities have indicated that just as good, if not better, results would probably be obtained with the latter charges, and at a considerable reduction in cost.

OPEN HOLE BLASTING

John A. Roos (44) has reported the use of home-made shaped charges as drilling aids in churn-drill holes.

Slow progress and frequent necessity of changing and sharpening bits when drilling ground containing a large number of boulders are well known to mining engineers. There are days when only a few feet of headway are made; more time and effort being devoted to changing and sharpening bits than in drilling holes.

Roos found that boulders too large to be driven aside can usually be shattered or broken by use of shaped charges without lifting the drive pipe. He formed his charges in small-diameter stovepipe or tall tin cans, using a section of another small tin can to give the charge a hemi-cylindrical cavity. A damp sand filler was added to the container above the charge of 60% gelatin to help sink the charge

through the muddy water in the hole.

In the opinion of Roos, the cost of drilling in hard, boulder-strewn ground can be reduced materially by the use of shaped charges.

Open hole and down hole charges are now being produced by at least one major explosives company.

BORING HOLES FOR POLES OR PYLONS

The possibility of using shaped charges to drive holes in soft and hard ground and in rock for the erection of poles or pylons has been investigated in England by Imperial Chemical Industries, Limited. (55) By using a 3-1/2-pound Pentolite, 80°, conical charge, it was found possible to produce holes in soil varying from 2-4 feet in diameter and 4-5 feet in depth. It appears that by selection of a suitable shaped charge, it is possible to drive, even in hard ground, holes of suitable size for the sinking of telephone poles or pylons.

Tests were also conducted on rock using somewhat heavier charges. Tabulated results indicate that the holes produced in rock were generally cone-shaped craters of greater diameter than depth, the depths ranging as high as 3 feet. In some cases it was necessary to fire two successive charges in the same position to attain reasonable crater depths.

Since pylon foundations are usually sunk in craters and then filled in with concrete, it was concluded that the craters produced in rock by shaped charges were satisfactory for this purpose. However, from the economic standpoint, shaped charges for the above types of work would only be acceptable for use in sites inaccessible to ordinary drilling machinery or where only a few holes might be required in remote areas. It is conceivable that charges for this type of work might be

justified in such applications as driving holes for pylons of power transmission towers which frequently traverse rough and remote areas, hole driving in mountainous and arctic areas, and possibly for use by coast and geodetic survey parties.

UNDERWATER CUTTING

The use of shaped charges for underwater cutting is feasible, provided the water is prevented from entering the cavity area, where its presence would practically nullify the jet effect. This is accomplished by the use of a water-tight standoff sleeve. Underwater charges are generally of the V-shaped linear type. Up to the present time, apparently little use has been made of shaped charges for underwater work, however, it would appear that they would be valuable in such applications as metal cutting in wreck disposal, gaining access to sunken ships through the hull, salvage work, clearing underwater obstacles, cable and chain cutting, severing bridge and pier supports, and the like, where underwater flame cutters would otherwise ordinarily be used.

In England, the Hayrick or "stook" charge was developed for such purposes during World War II. It consists of a linear V-shaped charge having an inflexible metal case. Imperial Chemical Industries, Limited has experimented with such charges made up in 1, 2, and 3 ft. lengths. When loaded with 1 pound of explosive per foot they can cut through 1 inch plate under water. Like all shaped charges, however, the cost of "stooks" is high.

It would be advantageous if underwater charges were equipped with a strong adhesive so that they could be easily attached to the object to

be attacked. The use of magnets may prove effective for this purpose in the case of metal targets. The DuPont Company has developed a simple and relatively inexpensive linear underwater charge which consists of two strips of metal soldered parallel to and tangent to the outside surface of a sealed length of pipe forming a trough. A waterproof explosive is then pressed into this trough. This provides a linear shaped charge having a hemispherical liner, the pipe acting as the liner and also providing a watertight standoff sleeve.

L. F. Porter (43) has patented an elongated, flexible, tubular shaped charge which may be useful in some types of underwater work. It employs a V-shaped metal liner housed in a rubber carrier. The liner is sectioned from the apex nearly to the base, at short intervals, thereby permitting the charge to be bent to follow the contour of the object being attacked.

SEISMIC PROSPECTING

Comparative tests of the use of shaped and unshaped charges for seismic prospecting have been reported by R. W. Lawrence of the Hercules Powder Company. (24) Charges of blasting gelatin and 60% seismograph gelatin, with lined and unlined conical cavities were fired with cased and uncased charges. The shaped charges were fired with and without standoff. Some 77 charges in all were fired, and a careful comparison of the seismographic records showed no difference in the results obtained from shaped charges and from normal charges.

Another series of trials was made during seismic prospecting operations in the ocean. Forty pounds of 7-inch diameter charges with 60 and 90° conical cavities were compared with similar unshaped charges.

Here again, no difference could be observed in the results.

DEMOLITION OF SCRAP METAL

In commercial metal salvage operations, the use of cutting torches is normally accompanied by a great consumption of time and materials. The possibility of using shaped charges to assist in the demolition of scrap metal to suitable sizes for re-smelting in furnaces has consequently been investigated. Tests were carried out in England (55) on portions of a furnace bottom using 3-3/4-lb. conical charges with a gelatin filler. Penetration was obtained, but the furnace bottom was not broken up by the charges nor was the depth of the resultant bore holes sufficient to permit their being loaded and shot.

It was therefore concluded that the shaped charge could not be profitably used for the demolition of scrap metal.

This writer feels, however, that the conclusion reached on the basis of the above tests is hardly justifiable. Penetration, rather than shattering of the heavy metal bottom should have been expected. It is still conceivable that shaped charges, probably of the linear type, may find specialized uses in reducing metal structures which are difficult of access to cutting torches.

RECOVERY OF WELL PIPE

The recovery of casings from wells scheduled for abandonment, as well as the recovery of upper portions of multiple strings in active wells, may become a major project in the event of a serious shortage of new casings.

The use of wedge-shaped charges for this purpose offers an un-

usually rapid and effective means of severing casing at any desired level. A comparable use is the cutting of drill pipe that has become stuck during drilling operations. The conventional method often requires several days to complete a single cutting operation, whereas with a shaped charge, this work can be done in minutes.

MISCELLANEOUS

METEOR STUDY

Meteor study has been enhanced by the use of shaped charges to create artificial meteors in the laboratory. (1) The metal jets formed have velocities comparable to real meteors which come to earth at speeds of about 11 miles per second. As the slugs rip through the air, the front end becomes incandescent from friction, and the metal vapor trails coming from the tip are clearly visible in super-high-speed photographs.

BLASTING CAPS

The shaped charge principle was for many years unwittingly incorporated into many commercial blasting caps by the indenting of a nipple into the bottom of the cap during its manufacture. Flash radiograph studies made of blasting caps in the process of detonation show the formation of the jet that contributes to their over-all effectiveness.

PUNCHING HOLES IN SHEET MATERIAL

A shaped charge capable of cutting a circular opening through sheet material has been patented by Mohaupt. (34) He suggests the possibility of its use in fighting fires. Assuming that firemen desire to get a stream of water into a burning building at a point where there are no doors or windows, a circular V-shaped charge could be used to punch a

hole, say 3 to 4 inches in diameter, through a wall or floor, after which a hose could be inserted through the opening. No mention is made, however, of the blast effect on personnel and buildings in the vicinity, nor of the attendant dangers of flame and heat on the explosive charge. The use of shaped charges in this case does not appear to be very practicable.

CABLE CUTTING

An apparatus for severing elongated articles such as cables, rods, chains, tubes, bars, ropes, pipes and the like has been patented by Davis. (11) One application where rapid cutting is highly desirable is in the case of gliders towed by airplanes, where immediate release of the glider may be essential.

ENGRAVING

An interesting application of the Munroe effect is made by the Trojan Powder Company of Allentown, Pa., in engraving steel paper weights. This is done largely from a novelty and advertising standpoint.

CUTTING TREES, PIPE, ETC.

Annular V-shaped charges have been designed, constructed and tested for cutting such items as trees, pipe, cylindrical tanks, etc. Although effective, it is doubtful that their use for such purposes will ever become widespread because of their relatively high cost and because of the accompanying blast problem.

INVESTIGATING STRENGTH PROPERTIES OF MATERIALS

The use of the hollow-charge principle for investigating strength properties of various materials when subjected to exceedingly high pressures has also been proposed. (2)

SUMMARY

1. The relative superiority of shaped charges and unshaped charges for secondary breakage of boulders is still somewhat of a matter of controversy. Shaped charges for this purpose have been recently put into production. However, it is the opinion of several experts based on various past investigations that an unshaped charge is just as effective and considerably cheaper than a shaped charge of the same external dimensions.

2. Jet perforators are excellent for perforating oil well casings. Gun perforators, although possessing inferior penetrating power than jet perforators, are still widely used primarily because of their cheaper cost. Jet perforators are used principally for the more difficult shots.

3. The tapping of open hearth furnaces with jet tappers is satisfactory and has several advantages over oxygen lancing. This is a new field for the shaped charge, and jet tappers are as yet only in limited production.

4. Shaped charges can be used to produce satisfactory drill holes for blasting. However, their high cost practically limits their use to cases in which the time of drilling is limited, or where only a few shot-holes are required in inaccessible positions or where power drilling equipment is not available. The use of glass liners permits the almost immediate loading of shot-holes with a secondary explosive.

5. The use of military-type demolition charges for drilling blast holes in underground mines is impractical.

6. The use of shaped charges in underground mines for reduction

of boulders in grizzlies and in scrams, as well as for breaking up finger hang-ups looks promising, though as yet has not been fully evaluated.

7. Large boulders encountered in open hole drilling can be economically shattered by the use of shaped charges.

8. It is possible to use shaped charges for driving holes of suitable size in the ground for the sinking of pylons or telephone poles. Satisfactory craters can also be produced in rock for the erection of pylons. However, economy, as well as blast effect, prohibit their general use for such purposes.

9. Linear shaped charges appear to have practical application in underwater cutting of metal plate such as in salvage work, wreck disposal, clearing underwater obstacles, etc.

10. Comparison of seismographic records show no difference in the results obtained from shaped charges and from normal charges.

11. The use of shaped charges for demolition of scrap metal does not at present appear to be profitable.

12. The shaped charge offers a rapid and effective means of severing well pipe and casings in recovery operations.

13. The shaped charge finds useful application in meteor study and in the rapid severing of glider tow lines. It may also prove useful in investigating high strength properties of materials.

CONCLUSION

In view of the fact that summaries have been included at the ends of the chapters dealing with the theories of jet formation and penetration, and with the military and industrial applications, no attempt will be made here to resummarize this work.

As yet, the only mathematical theories dealing with the shaped charge phenomenon which have appeared in the open literature or in categories less than confidential are those developed in the latter part of 1943 and the early part of 1944 by Birkhoff, MacDougal, Pugh and Taylor which were published in June 1948. These theories deal with the mechanisms of jet formation and penetration for wedge-shaped and conical liners, and are based upon the classical hydrodynamics of perfect fluids, which are applicable because the strength of the metals involved can be neglected at the high pressures encountered.

No mathematical theories have as yet been published for hemispherical liners. However, experimental techniques show that a different mechanism is operative here.

Although present mathematical theories have contributed much to our understanding of the phenomena involved, the theory has not as yet advanced to the stage where it can be directly and precisely applied in design calculations. The numerous variables involved in shaped charges are complexly interrelated, and as yet one cannot, by means of slide rule and formulae alone, set down the exact specifications for a so-called "ideal shaped charge" for a specific purpose. The designer can, however, armed with certain scaling laws and a mass of empirical data, set down a design which he knows will attain the performance desired.

In the case of military weapons, maximum penetrating efficiency must frequently be compromised in favor of other considerations. Nevertheless, the shaped charge principle has been incorporated into almost all types of weapons by all the major powers, and shaped charges have assumed an important role in the defeat of armor plate and reinforced concrete fortifications.

In the industrial field, shaped charges have not received such widespread application due primarily to the following reasons:

(a) The noise would be undesirable in many localities.

(b) Protection of personnel from blast and missile hazards would be required.

(c) The high cost of liners and cases makes shaped charges expensive as compared to current commercial explosives.

(d) Manufacturing and packaging costs are relatively high.

For the perforation of oil well casings, the shaped charge has proven itself superior to any other known means. Here, as in all of its other applications, its relatively high cost has generally caused it to be used only for the more difficult shots.

In secondary boulder blasting, where opportunity exists for large-scale use of a superior rock-breaking charge, it appears that the shaped charge is no better than a plain solid charge of the same explosive and similar external dimensions.

While a number of other practical applications have been developed, in many of these, use of shaped charges appears justifiable only in cases where conventional cutting or drilling equipment is not available, or where time for accomplishing the work is limited.

Investigation of possible commercial outlets is being continued by various commercial organizations and individuals, and more will undoubtedly be found.

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VITA

Amedeo Henry Galvani was born in Plymouth, Massachusetts, the son of Mr. and Mrs. Peter Galvani, on the 28th day of August, 1920.

He attended the Plymouth Public Schools after which he entered Tufts College at Medford, Massachusetts. There he studied engineering from 1938 to 1939. He then received an appointment to the U. S. Naval Academy at Annapolis, Maryland from which he was graduated in June 1942 with the degree of Bachelor of Science, and was commissioned an Ensign in the United States Navy.

For a short period following graduation, he taught naval ordnance at the naval indoctrination school for reserve officers at Dartmouth College, Hanover, N. H. During World War II and subsequent, he served aboard destroyers in the Pacific. In 1948, he was ordered to the U. S. Naval Postgraduate School at Annapolis for a three-year course in chemical ordnance. Two years of this course were spent at the Naval Postgraduate School, and in September 1950, he entered Lehigh University for the third year of the course and became a candidate for the degree of Master of Science in Chemistry. He is currently a Lieutenant Commander in the United States Navy.

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